# Probable Maximum Flood
# Willow Creek at Chain Lakes Reservoir

March 2002

**Environmental Operations Division**
**Hydrology Branch**
**Surface Water Section**

# Probable Maximum Flood Willow Creek at Chain Lakes Reservoir

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# EXECUTIVE SUMMARY

In support of the upcoming independent review of the Chain Lakes Reservoir, the Dam Safety and Water Projects Branch has requested the determination of the Probable Maximum Flood (PMF) at the structure. The design of the reservoir and its flood discharge facilities were originally based on hydrology studies done by the Prairie Farm Rehabilitation Administration (PFRA) in 1959. At the time of design the North and South Dams of the reservoir were classified in the "intermediate" size category, with "significant" hazard potential. Accordingly, the project was designed for a flood frequency of 0.5PMF. At that time a recommendation was made that the PMF be established using a method other than the Saskatchewan Nelson Basin Board (SNBB) procedures. With the addition of the Pine Coulee Diversion Works downstream of the South Dam, the facility has been reclassified as a "very high" consequence structure whose failure would lead to loss of life and large economic losses. Therefore, in accordance with the Canadian Dam Safety Association's (CDA) Dam Safety Guidelines the Inflow Design Flood (IDF) for the Chain Lakes Reservoir has been defined as the PMF.

The Probable Maximum Precipitation (PMP) used to determine the PMF at the Chain Lakes Reservoir is based on the World Meteorological Organization (WMO) guidelines. The PMP is then applied to the Willow Creek basin, and the PMF hydrograph to the reservoir is computed using the U.S. Army Corps of Engineers hydrological model, "Streamflow Synthesis and Reservoir Regulation (SSARR)", calibrated to the historical flood events in the basin.

The computed PMP of 48-hour duration is 420mm. The PMF peak is 916 $m^3/s$.

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# ACKNOWLEDGEMENTS


| | |
|---|---|
| Chacko Abraham | Preparation of data files for use in SSARR calibration |
| Andy DeBoer | Conducted a review of the final report |
| Sean Douglas | Guidance through the PMP calculations, GIS work and SSARR calibrations |
| Ray Keller | Provided the snow-pillow and snow-course data |
| John Taggart | Conducted the review of the SSARR calibrations as well the final report |

# LIST OF ABBREVIATIONS AND CONVERSION FACTORS

Metric units of measurement are preferred and have been used wherever possible. In some circumstances, such as displaying output from the SSARR model, it is more convenient to display U.S. Imperial units since those are the units used by the model.

## Abbreviations

| | |
|---|---|
| cubic metres per second | $m^3/s$ or cms |
| cubic metres per second per square kilometre | $m^3/s/km^2$ |
| cubic decametres | $dam^3$ |
| millimetres | mm |
| metres | m |
| square kilometres | $km^2$ |
| kilometres | km |
| millibars | mb |
| cubic feet per second | $ft^3/s$ or cfs |
| cubic feet per second per square mile | cfs/sq.mi. |
| acre-feet | ac-ft |
| feet | ft |
| square miles | sq.mi.or $mi^2$ |

## Conversion Factors

| | | | | |
|---|---|---|---|---|
| cubic metres per second | × | 35.3146 | = | cubic feet per second |
| cubic metres per second per square kilometre | × | 91.4646 | = | cubic feet per second per square mile |
| cubic decametres | × | 0.8107 | = | acre-feet |
| millimetres | × | 0.03937 | = | inches |
| metres | × | 3.28083 | = | feet |
| square kilometres | × | 0.38610 | = | square miles |
| kilometres | × | 0.6215 | = | miles |

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# 1.0 INTRODUCTION

## 1.1 Background

The two dams that form the Chain Lakes Reservoir are located about 35 km west of Nanton, in Southwest Alberta. The North Dam discharges to Meinsinger Creek a tributary of the Highwood River. The South Dam, on Willow Creek is a tributary of the Oldman River. The reservoir, which extends in a north south direction, straddles the divide between Meinsinger Creek and Willow Creek. The location of the Chain Lakes Reservoir drainage basin, with a contributing drainage area of 210 km², and the two dams is shown in Figure 1.1. The headwaters of this system originate in the Plateau Mountains of the Livingstone Mountain range of the Rocky Mountains. The Porcupine Hills foothills define the basin boundary to the south. Local relief in the mountains is extreme with the river valley at approximately 1280.2 meters and the surrounding mountain peaks reaching elevations of approximately 2316.5 meters (Figure 1.2).

The basin has been modeled to include two sub-basins. The first is upstream of the Water Survey of Canada (WSC) hydrometric gauge 05AB028 Willow Creek above Chain Lakes Reservoir and the second represents the local inflow from the area surrounding the reservoir (Figure 1.3). There is a WSC level gauge on Chain Lakes - WSC 05AB037 with historical and real-time data.

Flood discharge facilities at the site consist of an overflow spillway located on the right abutment of the South Dam, and the riparian outlets at each dam. The spillway consists of a weir control section, a chute and a stilling basin. The crest of the spillway is at the reservoir Full Supply Level (FSL) of 1297.1 meters.

In support of the Willow Creek water storage feasibility studies completed in the mid- 1980's the Hydrology Branch of Alberta Environment completed a Probable Maximum Flood (PMF) study for the Willow Creek Basin draining to the town of Claresholm, see Reference 2. Probable Maximum Precipitation (PMP) estimates were developed using World Meteorological Organization (WMO) procedures and were routed through the basin using the U.S. Army Corps of Engineers SSARR hydrological model. For modeling purposes the study area was separated into five sub-basins, the first of which was the area draining to the WSC gauge Willow Creek above Chain Lakes Reservoir.

The WSC gauge sub-basin PMP and PMF estimates resulting from the mid-1980's study are as follows.

- 1986 Study PMP 442 mm
- 1986 Study PMF 764 $m^3/s$

In 1983 and 1979 PMF studies were completed for the entire area draining to the Chain Lakes Reservoir using the procedure outlined by the Saskatchewan Nelson Basin Board (SNBB). The estimated PMF values for these two studies are as follows.

- 1983 Study PMF 820 $m^3/s$
- 1979 Study PMF 425 $m^3/s$

## 1.2 Objective

The objective of this report is to provide the probable maximum flood for the Chain Lakes Reservoir. Specifically, this report includes:

- Derivation of the PMP for the two sub-basins.
- Calibration of the SSARR model for the Willow Creek above Chain Lakes Reservoir using the large event hydrological and meteorological data.
- Derivation of the PMF for the Chain Lakes Reservoir through the use of SSARR modeling.

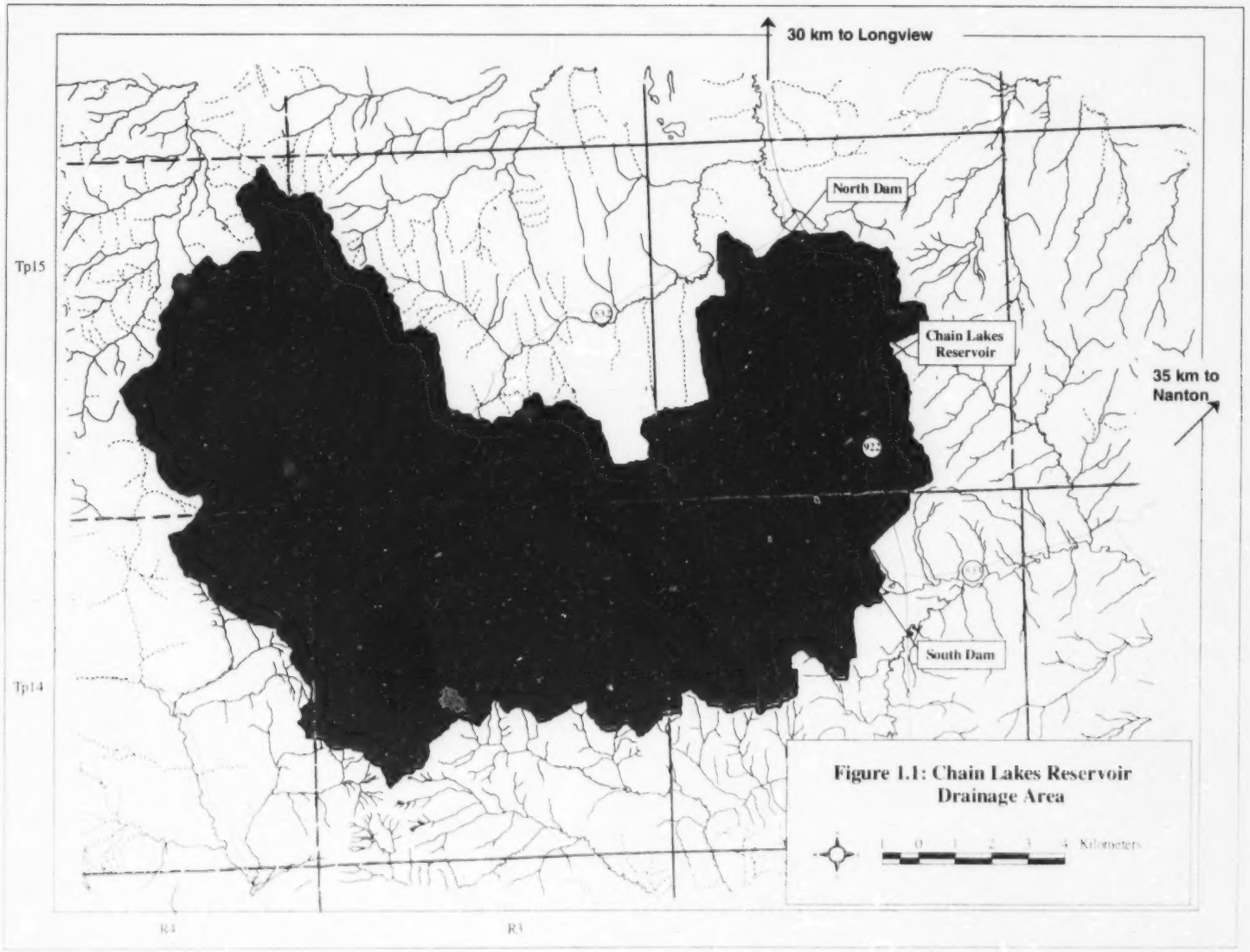



**Figure 1.1: Chain Lakes Reservoir Drainage Area**

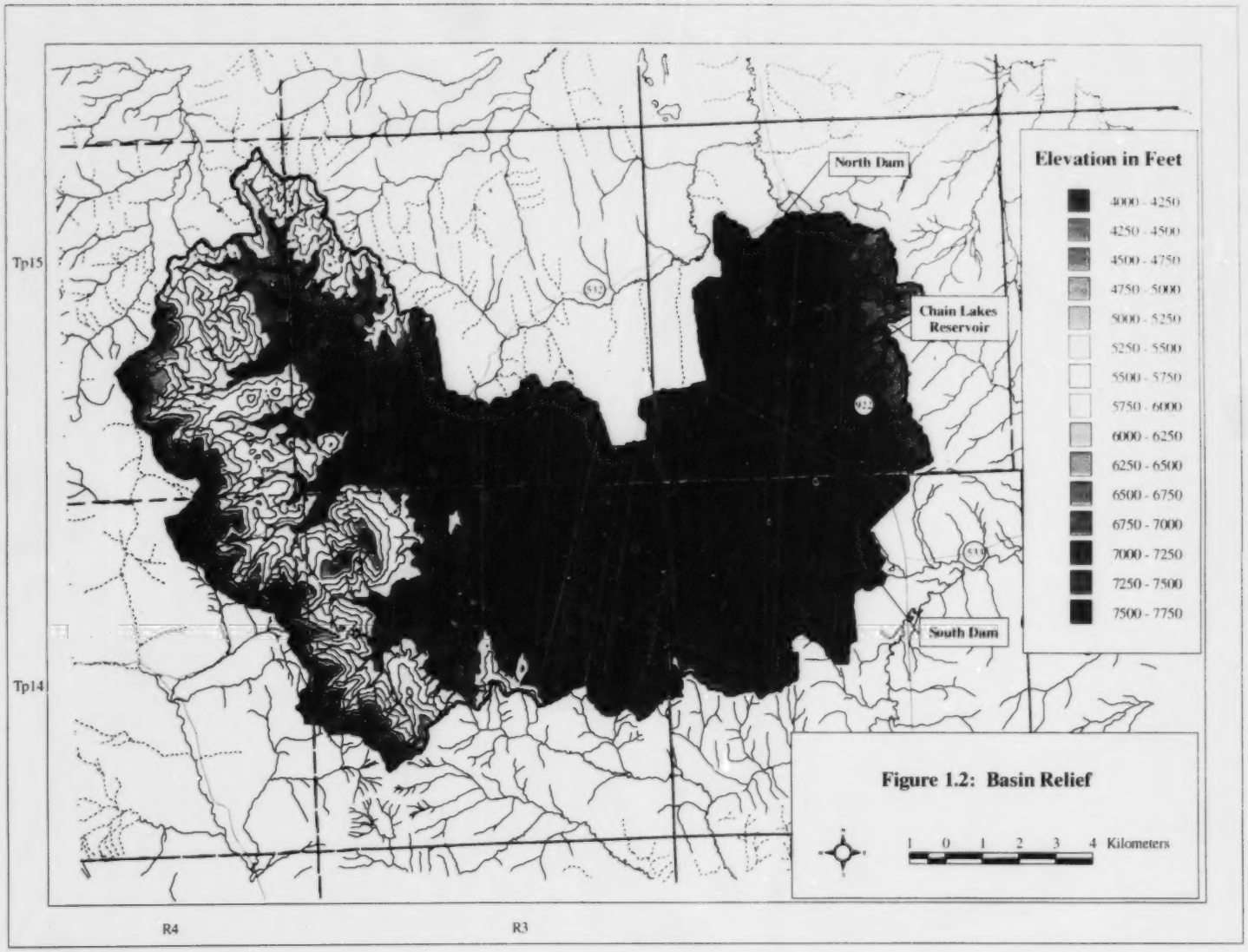



**Figure 1.2: Basin Relief**

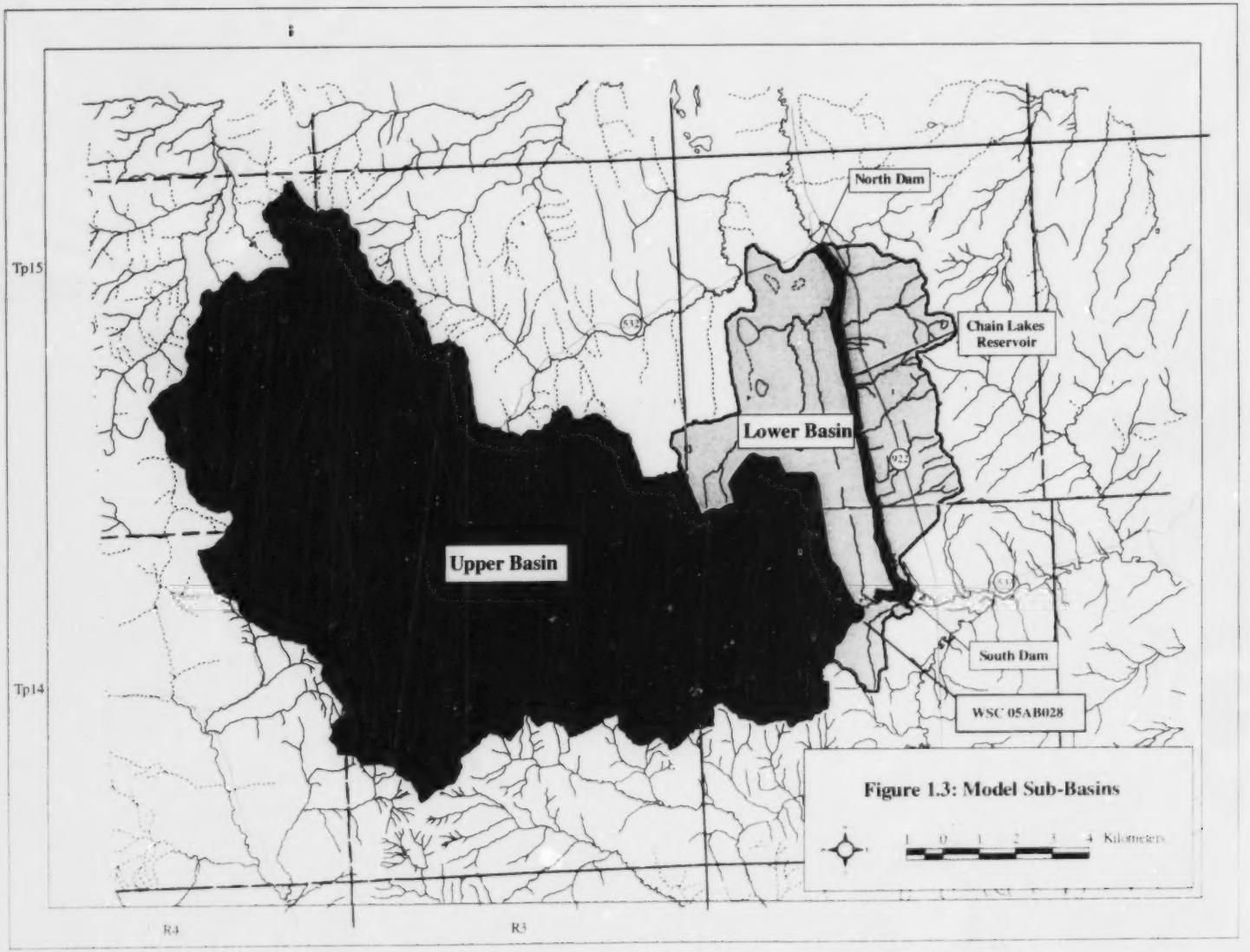



**Figure 1.3: Model Sub-Basins**

# 2.0 PROBABLE MAXIMUM PRECIPITATION

## 2.1 Definition of PMP

Probable Maximum Precipitation (PMP) is defined as the greatest depth of precipitation for a given duration, which is meteorologically possible for a given basin at a given time of year, with no allowances made for long-term climatic trends (Reference 1). Within this report, a meteorological approach is used for the computation of the PMP. The method is indirect, and is based on the maximization and transposition of the largest rainstorms that have occurred in the vicinity of the study area during the period of rainfall records. For more details, the reader is referred to Reference 2.

## 2.2 Meteorology of Major Storms

Precipitation data for southwestern Alberta indicate an annual rainy season beginning in mid-May and persisting through to mid July. While storms in the area can occur as early as mid-April and as late as September, most major storms have occurred during the May-July period when atmospheric conditions are historically most favourable.

The general atmospheric conditions that produce these major storms follow a fairly regular pattern. By June, the southern half of the United States and the Gulf of Mexico have warmed appreciably. Air masses from these regions are therefore capable of carrying considerably larger quantities of water vapour than is possible earlier in the season. These moisture-laden air masses begin spreading over the Great Plains to the north-northwest, reaching the eastern slopes of the Continental Divide without any appreciable upwind moisture depletion. The inflow of the warm moist air from the Gulf is further enhanced by one or more cold lows off the West Coast, which begin moving eastward across British Columbia and the State of Washington. In June, these cold lows have lost little of their late winter and early spring energy. The warm moist air becomes involved in energetic counter clockwise circulation around the lows and is forced upslope against the Rocky Mountains from an east to northeast direction. The large quantities of rainfall associated with these conditions are the result of the two rain producing mechanisms: the convergence around the cold low, and the lifting of the air masses along the mountain slopes.

## 2.3 Convergence PMP

### 2.3.1 1000 mb Convergence PMP

Seven major convergence storms occurring in areas of Alberta deemed to be transferable to the study area have been maximized based on the 12-hour maximum persisting dewpoint procedure and transposed to 1000 mb level, see Reference 7. Of the seven storms analyzed in Reference 7, the 1973 storm produces the largest precipitation values when maximized. The 1000 mb convergence PMP for the Willow Creek above Chain Lakes Reservoir is derived by maximizing and transposing the June 15, 1973 convergence storm for different durations (Appendix 4), and extracting the highest value of precipitation for each duration for a 210 km² area. The resulting 1000 mb convergence PMP for the project location is presented graphically in Figure 2.1 and summarized numerically in Tables 2.1 and 2.2.

**Table 2.1: Accumulated 1000 mb Convergence PMP by Variable Dewpoint Procedure for 210 km² Area**

| Hours | 0-6 | 6-12 | 12-18 | 18-24 | 24-30 | 30-36 | 36-42 | 42-48 |
|---|---|---|---|---|---|---|---|---|
| PMP (mm) | 182 | 293 | 374 | 435 | 467 | 493 | 498 | 502 |

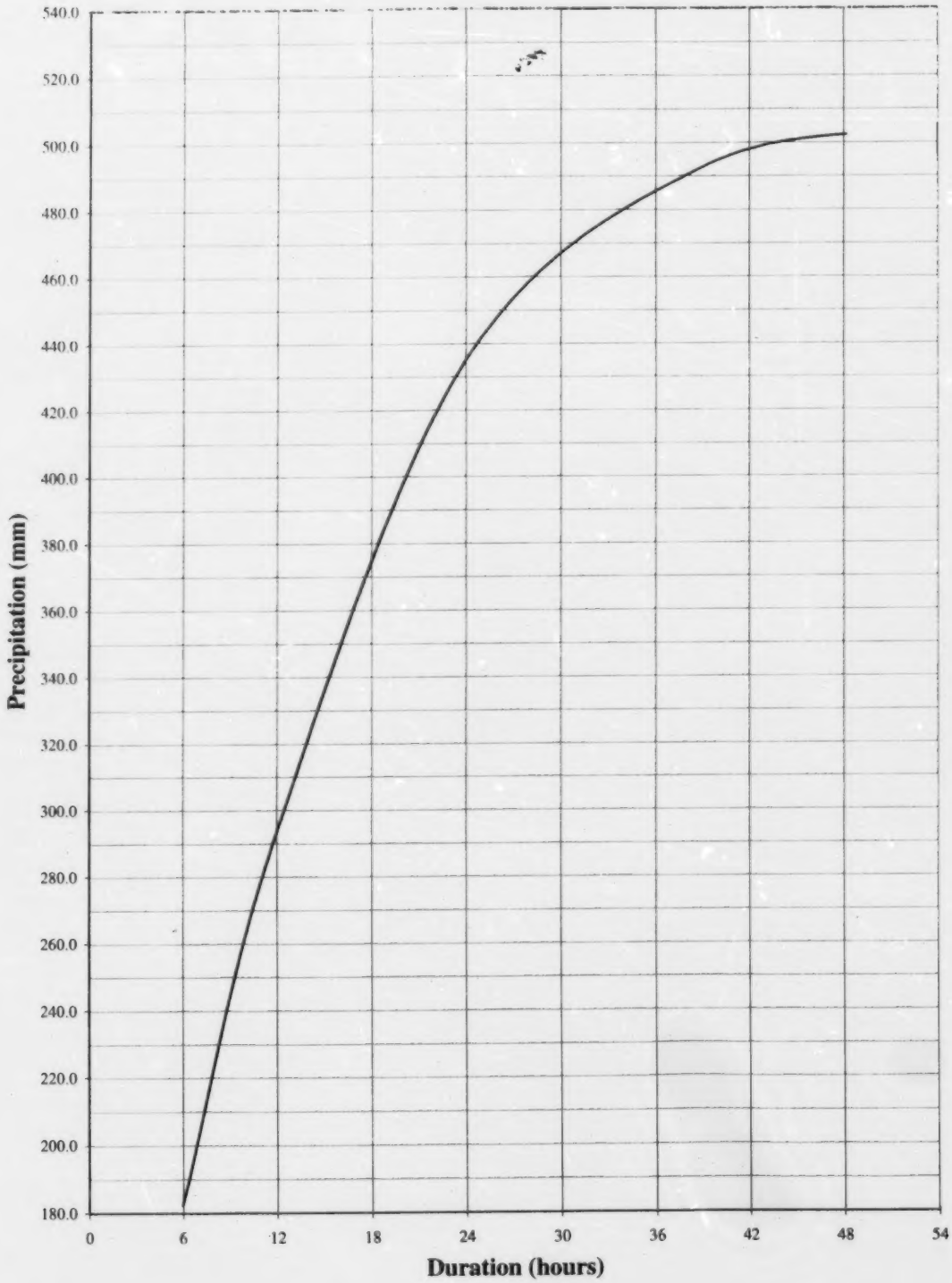
**Table 2.2: Incremental 1000 mb Convergence PMP by Variable Dewpoint Procedure for 210 km² Area**

| Hours | 0-6 | 6-12 | 12-18 | 18-24 | 24-30 | 30-36 | 36-42 | 42-48 |
|---|---|---|---|---|---|---|---|---|
| PMP (mm) | 182 | 111 | 81 | 61 | 32 | 26 | 5 | 4 |

### 2.3.2 Convergence PMP for SSARR Model

The convergence PMP presented in Table 2.2 is for the 1000 mb surface level. In estimating the PMP for higher elevations it is necessary to deplete the amount of moisture, by the moist adiabatic rate, from the 1000 mb surface level up to the elevation where the convergence PMP is to be applied. Figures 1.2 and 1.3 show the different basins and the elevation contours, and Table 2.3 summarizes the area percentages for the different elevation of each sub-basin. The depleted incremental convergence PMP for different elevations is listed in Table 2.4. The convergence precipitation at different elevations is calculated using the relationship as given in Equation 1:

**Figure 2.1: 1000 mb Convergence PMP by Variable Dewpoint for an area of 210 km²**



**Equation 1**.....

$$P_{elev} = \frac{(T - x)}{T} \times P_{1000}$$

Where,

$P_{elev}$ = precipitation at a specific elevation above 1000 mb.

$P_{1000}$ = precipitation at the 1000 mb elevation.

T = total precipitable water in column of air between 1000 mb and nodal surface (300 mb level) as a function of the maximum 1000 mb dew point temperature (22.5 °C due to June event time).

X = precipitable water (mm) between 1000 mb surface and indicated height above that surface in a pseudo-adiabatic atmosphere as a function of the 1000 mb dew point temperature associated with each specific storm duration.

Combining Table 2.3 (Sub-Basin Area Percentage) with Table 2.4 (Incremental Convergence PMP) by summing the precipitation for each elevation percentage yields the resulting average incremental convergence PMP of each sub-basin. Table 2.5 summarizes the results of this calculation

**Table 2.3: Sub-Basin Area Percentage for Different Elevations**

| Elevation (ft) | Elevation (m) | Basin | | | |
|---|---|---|---|---|---|
| | | Upper Basin | | Lower Basin | |
| | | Area (km²) | % | Area (km²) | % |
| 4200 | 1280 | 2.7 | 1.6 | 17.0 | 35.8 |
| 4400 | 1341 | 10.4 | 6.4 | 15.9 | 33.5 |
| 4600 | 1402 | 18.5 | 11.4 | 8.5 | 17.8 |
| 4800 | 1463 | 26.6 | 16.4 | 4.1 | 8.6 |
| 5000 | 1524 | 22.3 | 13.7 | 1.7 | 3.6 |
| 5200 | 1585 | 20.6 | 12.7 | 0.3 | 0.6 |
| 5400 | 1646 | 16.2 | 10 | | |
| 5600 | 1707 | 14.3 | 8.8 | | |
| 5800 | 1768 | 9.3 | 5.8 | | |
| 6000 | 1829 | 6.4 | 3.9 | | |
| 6200 | 1890 | 4.8 | 3 | | |
| 6400 | 1951 | 3.5 | 2.1 | | |
| 6600 | 2012 | 2.8 | 1.7 | | |
| 6800 | 2073 | 2 | 1.2 | | |
| 7000 | 2134 | 1.3 | 0.8 | | |
| 7200 | 2195 | 0.5 | 0.3 | | |
| 7400 | 2256 | 0.2 | 0.1 | | |
| 7600 | 2316 | 0.1 | 0.1 | | |
| | Sum | 162.4 | 100.0 | 47.5 | 100.0 |

**Table 2.4: Incremental Convergence PMP (mm) at Elevation Indicated**

| Elevation (ft) | 0 | 4200 | 4400 | 4600 | 4800 | 5000 | 5200 | 5400 | 5600 | 5800 |
|---|---|---|---|---|---|---|---|---|---|---|
| Elevation (m) | 0 | 1280 | 1341 | 1402 | 1463 | 1524 | 1585 | 1646 | 1707 | 1768 |
| Hours | PMP (mm) | | | | | | | | | |
| 0-6 | 182 | 121 | 118 | 116 | 114 | 112 | 109 | 107 | 104 | 102 |
| 6-12 | 111 | 74 | 72 | 70 | 69 | 68 | 67 | 65 | 63 | 62 |
| 12-18 | 81 | 54 | 53 | 52 | 51 | 50 | 49 | 48 | 47 | 46 |
| 18-24 | 61 | 41 | 40 | 39 | 39 | 38 | 38 | 37 | 36 | 36 |
| 24-30 | 32 | 22 | 22 | 21 | 21 | 21 | 20 | 20 | 19 | 19 |
| 30-36 | 26 | 18 | 17 | 17 | 17 | 16 | 16 | 16 | 16 | 15 |
| 36-42 | 5 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 3 | 3 |
| 42-48 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 |

**Table 2.4: Incremental Convergence PMP (mm) at Elevation Indicated Cont'd**

| Elevation (ft) | 6000 | 6200 | 6400 | 6600 | 6800 | 7000 | 7200 | 7400 | 7600 |
|---|---|---|---|---|---|---|---|---|---|
| Elevation (m) | 1829 | 1890 | 1951 | 2012 | 2073 | 2134 | 2195 | 2256 | 2316 |
| Hours | PMP (mm) | | | | | | | | |
| 0-6 | 99 | 97 | 94 | 92 | 90 | 88 | 86 | 85 | 83 |
| 6-12 | 60 | 59 | 57 | 56 | 55 | 54 | 53 | 52 | 50 |
| 12-18 | 45 | 44 | 43 | 42 | 41 | 40 | 40 | 39 | 38 |
| 18-24 | 35 | 34 | 33 | 32 | 32 | 31 | 30 | 30 | 30 |
| 24-30 | 19 | 18 | 18 | 17 | 17 | 17 | 16 | 16 | 16 |
| 30-36 | 15 | 15 | 14 | 14 | 14 | 13 | 13 | 13 | 13 |
| 36-42 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| 42-48 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |

**Table 2.5: Average Incremental Convergence PMP (mm) of Each Sub-Basin**

| Sub Basin Time | Upper Basin | Lower Basin | Area Weighted Average |
|---|---|---|---|
| 0-6 | 109 | 118 | 111 |
| 6-12 | 66 | 72 | 67 |
| 12-18 | 50 | 53 | 51 |
| 18-24 | 38 | 40 | 38 |
| 24-30 | 20 | 22 | 20 |
| 30-36 | 16 | 17 | 16 |
| 36-42 | 3 | 4 | 3 |
| 42-48 | 3 | 3 | 3 |
| Storm | 304 | 328 | 310 |

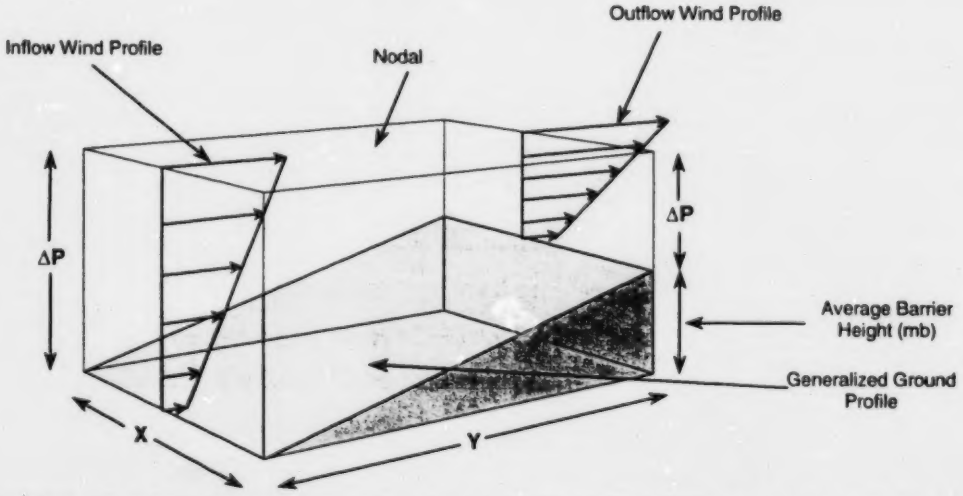
## 2.4 Orographic PMP

In the absence of pure orographic storm data, the orographic component of the PMP may be calculated by maximizing the precipitation from a combined storm (a precipitation event containing both convergence and orographic components) and subtracting out the previously calculated convergence component of the PMP.

### 2.4.1 Orographic Precipitation Isohyets

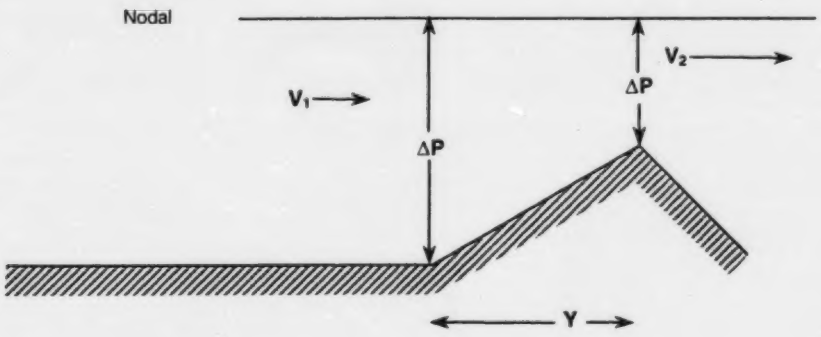
When computing the orographic component of the PMP the orographic separation method is used (Reference 1). The distribution of the orographic component (orographic precipitation isohyets) is usually assessed by applying a two-dimensional wind model to cross-sectional or computational strips of the area of interest. The models consider the two-dimensional flow of air in laminar layers of a vertical plane at right angles to the mountain ridge as shown in Figure 2.2A. Precipitation is computed as the difference between the water vapour inflow for each layer at the base of the mountain and the water vapour outflow above the ridge. The model, however, requires data of upper level winds, moisture and temperature.

**Figure 2.2A: Simplified Inflow and Outflow Wind Profiles over a Mountain Barrier**




In the absence of upper level data, as is the case for major storms in Alberta, the model may be simplified by assuming that the air is saturated and that the temperature decreases along the rising streamlines at the moist adiabatic rate. With these simplifying assumptions, the flow may be treated as a single layer of air between the ground and the nodal surface (300 mb level), as shown in Figure 2.2B.

**Figure 2.2B: Single Layer, Laminar Flow Wind Model**




The rate of precipitation is then:

**Equation 2**..... $$R = \frac{\vec{V}_1 W_1 - \vec{V}_2 W_2}{Y}$$

**Equation 3**..... $$\vec{V}_1 \Delta P_1 = \vec{V}_2 \Delta P_2 = \text{Constant}$$

where,

| | |
|---|---|
| R | = precipitation rate in the distance of Y in mm/hr. |
| $\vec{V}_1, \vec{V}_2$ | = mean inflow and outflow wind speed in km/hr. |
| $W_1, W_2$ | = inflow and outflow precipitable water in mm. |
| Y | = horizontal distance in km. |
| $\Delta P_1, \Delta P_2$ | = inflow and outflow pressure differences in mb. |

The relative distribution of orographic precipitation for the Willow Creek basin is assessed for an inflow of air from the three potential directions, the east, north-east and north-north-east. To carry out the assessment, the basin is first divided into 1 km wide computational strips parallel to the direction of the inflowing air. The single layer laminar flow model is applied to the computational strips, using the 1:50 year mean wind velocity for the 915 meter level (64.4 km/h) and the June 1:100 year - 12 hour persisting dewpoint temperature at 1000 mb (22.5 °C). The results of this application are the indicative isohyets of orographic precipitation.

The inflow direction producing the greatest orographic precipitation was that from the north-east. The indicative 6-hour orographic PMP isohyets derived using the north-east direction single layer model are shown in Figure 2.3. The isohyetal values presented are indicators of

the relative distribution of orographic precipitation and are not to be confused with the absolute values of precipitation. The single layer laminar flow model considers the flow of air in a vertical plane at right angles to the mountain ridge. Since the model does not consider breaks in ridges or passes, which may allow air to flow around rather than over a ridge and thus reduce the amount of lifting and resulting precipitation, the use of maximum wind and moisture in the model can lead to an over-estimation of the PMP. To avoid this risk, the isohyets of orographic PMP computed are used only as indicators as to the relative distribution of the orographic PMP.

### 2.4.2 Orographic PMP for SSARR Model

As outlined in the previous section, the single layer, laminar flow model can lead to an over-estimation of orographic PMP. Therefore, the isohyets of orographic PMP computed in the previous section are used only as indicators of the orographic PMP's relative distribution. Actual values of orographic PMP are estimated by computing the orographic PMP from observed orographic storms and adjusting this value for the Willow Creek basin on the basis of the orographic isohyets established by the model.

As determined in Reference 7 the June 5-8, 1964 Montana storm provides the highest values of combined precipitation for all durations. The values of the 6-hour incremental combined precipitation for the storm center of 26 km² (area of storm center of 1964 storm) were calculated in Appendix 4. The storm centre predicted by the laminar flow model is only slightly smaller than the 1964 storm centre and thus the analysis performed in Appendix 4 is still valid. The increase in precipitation, resulting from the reduction of the storm centre, is not significant in this case due to the negligible slope at the lower end of the 1964 storm Depth-Area-Duration Curve. Therefore, the 6-hour incremental values of combined precipitation are maximized for moisture and transposed directly to the areas within the 160 mm isohyets in the Willow Creek basin. The maximized 6-hour incremental combined precipitation is listed in Table 2.6.

The orographic component of the combined PMP is determined by assuming that the computed values of combined PMP are representative of the total PMP for the largest isohyet within Figure 2.3 and by subsequently removing the convergence PMP from the combined total. Given the average pressure level of the 1964 storm centre to be 785 mb (7000 ft), the convergence and orographic PMP values associated with the 160 mm isohyet are computed as indicated in Table 2.6.

**Table 2.6: Maximized 6-hour Incremental Combined, Convergence and Orographic PMP for the Storm Center of 26 km² for the June 1964 Storm**

| Hours | 0-6 | 6-12 | 12-18 | 18-24 | 24-30 | 30-36 | 36-42 | 42-48 |
|---|---|---|---|---|---|---|---|---|
| **Combined PMP (mm)** | 221 | 200 | 116 | 76 | 45 | 18 | 5.4 | 2.0 |
| **Convergence PMP (mm)** | 91 | 55 | 39 | 32 | 21 | 8 | 4.7 | 1.7 |
| **Orographic PMP (mm)** | 130 | 144 | 77 | 44 | 24 | 10 | 0.7 | 0.3 |

The values in Table 2.6 were assumed to be the average orographic PMP for the area within the 160 mm isohyets in the Upper Willow Creek basin. The average incremental orographic PMP values associated with the other isohyets were estimated using the following equation:

**Equation 4**.....

where,

$$P_{n,t} = \frac{(R_{avg})}{160} P_{160,t}$$

$R_{avg}$ = average precipitation depth between two isohyets.

$P_{n,t}$ = average incremental orographic PMP in mm of a given duration t for the area between two isohyets.

$P_{160,t}$ = average incremental orographic PMP in mm of a given duration t for the area within 160 mm isohyets as provided in Table 2.6.

Based on the values of the incremental orographic PMP for different isohyetal intervals, as computed by the above equation and the corresponding precipitation covered areas in each of the sub-basins as shown in Figure 2.3, the values of the resulting average incremental orographic PMP for each sub-basin for the SSARR Model were computed as listed in Table 2.7.

**Table 2.7: Average Incremental Orographic PMP of Each Sub-Basin**

| Sub Basin Time | Upper Basin | Lower Basin | Area Weighted Average |
|---|---|---|---|
| 0-6 | 38.4 | 16.5 | 33 |
| 6-12 | 42.7 | 18.3 | 37 |
| 12-18 | 22.8 | 9.8 | 20 |
| 18-24 | 13.1 | 5.6 | 11 |
| 24-30 | 7.2 | 3.1 | 6 |
| 30-36 | 3.0 | 1.3 | 3 |
| 36-42 | 0.2 | 0.1 | 0.2 |
| 42-48 | 0.1 | 0 | 0.1 |
| Storm | 127.5 | 54.6 | 111 |

## 2.5 Total PMP for SSARR Model

The total average incremental PMP for each SSARR model sub-basin were estimated as the sum of the average incremental convergence PMP in Table 2.5 and the average incremental orographic PMP in Table 2.7. The final results are listed in Table 2.8.

**Table 2.8: Total Average Incremental PMP in mm of Each Sub-Basin for the SSARR Model**

| Sub Basin Time | Upper Basin | Lower Basin | Area Weighted Average |
|---|---|---|---|
| 0-6 | 147 | 135 | 144 |
| 6-12 | 109 | 90 | 105 |
| 12-18 | 72 | 63 | 70 |
| 18-24 | 51 | 46 | 49 |
| 24-30 | 27 | 25 | 27 |
| 30-36 | 19 | 18 | 19 |
| 36-42 | 4 | 4 | 4 |
| 42-48 | 3 | 3 | 3 |
| Storm | 431 | 383 | 420 |

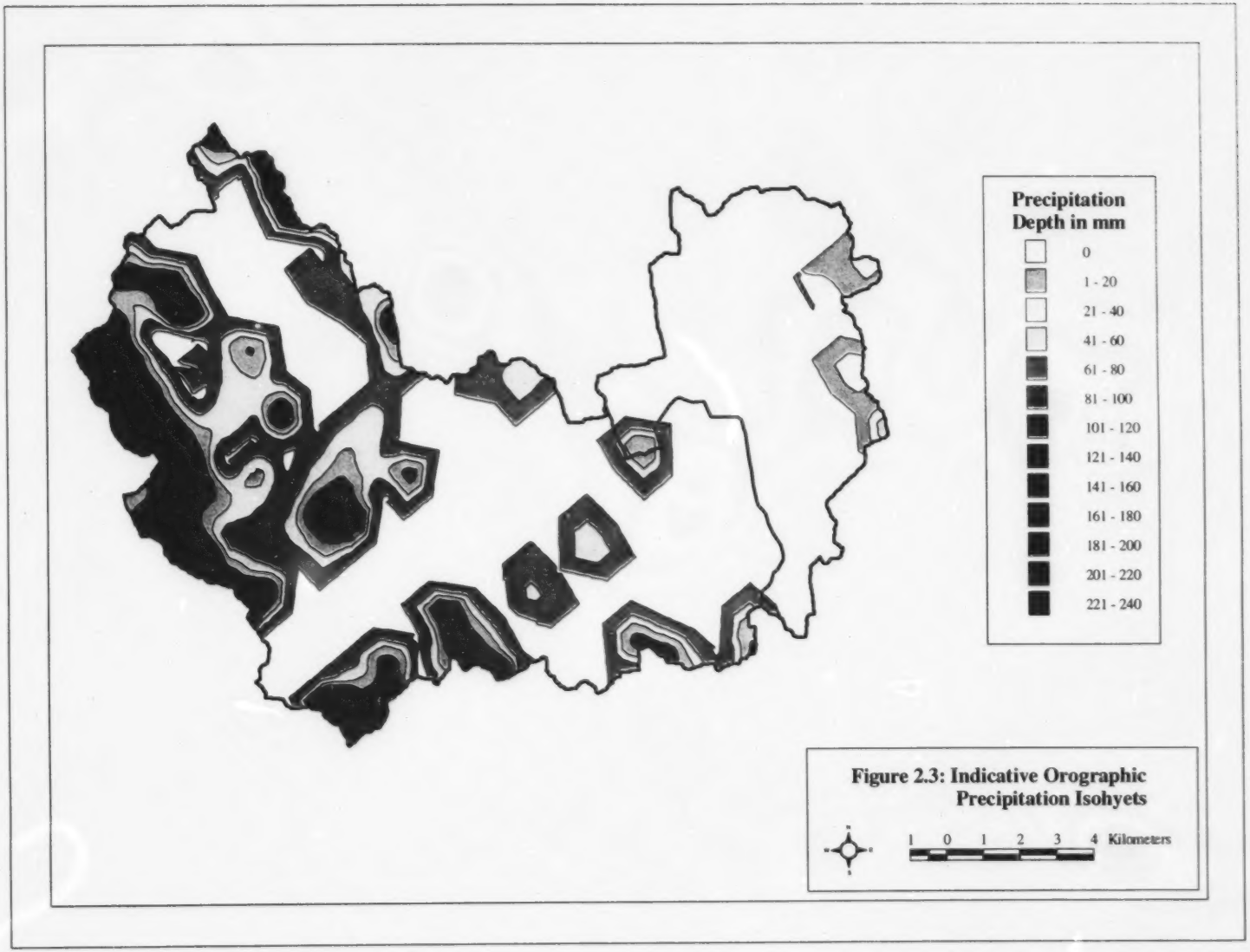



**Figure 2.3: Indicative Orographic Precipitation Isohyets**

# 3.0 INITIAL SNOWPACK AND MELTRATE CONDITIONS FOR THE PMF

Snowmelt is incorporated into the analysis based on the following assumptions:

- There is no snow below 1680 meters (5500 feet), as discussed in Reference 7.
- The accumulated snowpack will melt based on the prevailing temperatures during the PMF event.

Based on the area-elevation relationship of the Upper portion of the Willow Creek basin, there is approximately 53 square kilometers (20 square miles) of the basin covered in snow prior to the application of the PMP.

The amount of melt occurring during the PMP event is calculated within the SSARR model using the SSARR snowmelt relationships provided in Appendix 1. The meltrate is a function of the degree-days based on the air temperature. During the PMP event the air mass is fully saturated. As the dew point temperatures are already maximized it is not physically reasonable to expect higher air temperatures to occur during the event. Therefore, the maximized dew point temperatures are adjusted for the basin elevation using the pseudo-adiabatic lapse rate. The degree-days are then based on these temperatures and lapse rate and the snowmelt is computed in the standard manner.

# 4.0 PROBABLE MAXIMUM FLOOD

## 4.1 Conversion of PMP and Snowpack to PMF

Having derived the PMP and initial snowpack conditions, this section of the report deals with the routing of the PMP and snowpack off the watershed to produce the Probable Maximum Flood (PMF) at the Chain Lakes Reservoir. The rainfall-runoff model chosen to convert the PMP to the PMF was developed by the U.S. Army Corps of Engineers and is called the "Streamflow Synthesis and Reservoir Regulation" or "SSARR" model (Reference 3). This model is chosen because of its ability to incorporate snowmelt, its adaptability to the physical characteristics of the basin and its ease of calibration to recorded historical events.

## 4.2 Calibration of the SSARR Model

A SSARR model, calibrated in 1995, of the Willow Creek basin above the Chain Lakes Reservoir is currently in use by the Hydrology/Forecasting Section of Alberta Environment. For the purpose of this PMF analysis, this model has been refined to better define the upper range of the SSARR model relationships. These refinements are designed to provide the best possible calibration for extreme precipitation events and to ensure a realistic routing of the runoff from the watershed.

The general procedure for the calibration is to compare the simulated runoff of the SSARR model for the 1975, 1981 and 1990 storms to the recorded streamflow information for the same time period at the WSC gauge Willow Creek above Chain Lakes (05AB028). By maintaining a physical sense within the relationships of the model and by iterating between simulated and recorded runoff, the optimum relationships are determined.

The existing SSARR model for the Willow Creek basin above the Chain Lakes Reservoir is comprised of a single sub basin, referred to as the Upper Basin, which is modelled using both a snow covered area and a snow free area. Typically, SSARR sub-basins, while made to correspond to the locations of hydrometric stations for computational convenience, are meant to represent basin areas that differ in physiographic and meteorological conditions. For the purposes of this study an additional sub-basin, referred to as the Lower Basin, representing the low relief area that adds local inflow to the Chain Lakes Reservoir was added.

The two basins are:

| | | |
|---|---|---|
| Upper Willow Creek sub-basin | 162 km² | UWILLSCA, UWILLSFA |
| Lower Willow Creek sub-basin | 48 km² | LWILLSCA, LWILLSFA |

The following are the hydrometric and meteorologic stations used in the calibration, their locations are shown on Figure 4.1:

**Hydrometric Stations**

| | | |
|---|---|---|
| • Willow Creek above Chain Lakes | WSC – 05AB028 | - RWILCHAN |
| • Chain Lakes Reservoir near Nanton | WSC – 05AB037 | |

**Meteorologic Stations**

- Upper and Lower Basins

| | | |
|---|---|---|
| • STRE | Streeter | Precip, Temp |
| • PEKI | Pekisko | Precip |
| • HBLO | Hailstone Butte | Precip, Temp |
| • PORC | Porcupine | Precip |
| • LIVI | Livingstone Airfield | Precip, Temp |
| • CALG | Calgary | Precip, Temp |
| • WCRS | Westcastle Ranger Station | Precip, Temp |

A schematic flowchart of the SSARR model for the Willow Creek basin is provided in Figure 4.2.

The methodology for calibrating the SSARR model for the Willow Creek basin can be summarized in the following steps:

1. Compute local runoff hydrographs for the sub-basin areas from the historical flood records of the hydrometric stations.
2. Introduce to the model the historical precipitation, temperature and evaporation data along with presumptive estimates of hydrologic relationships for the sub-basin areas under consideration.
3. Calculate and compare the results of SSARR model simulation with the recorded local runoff hydrographs to test the validity of the presumptive estimates of hydrologic relationships.

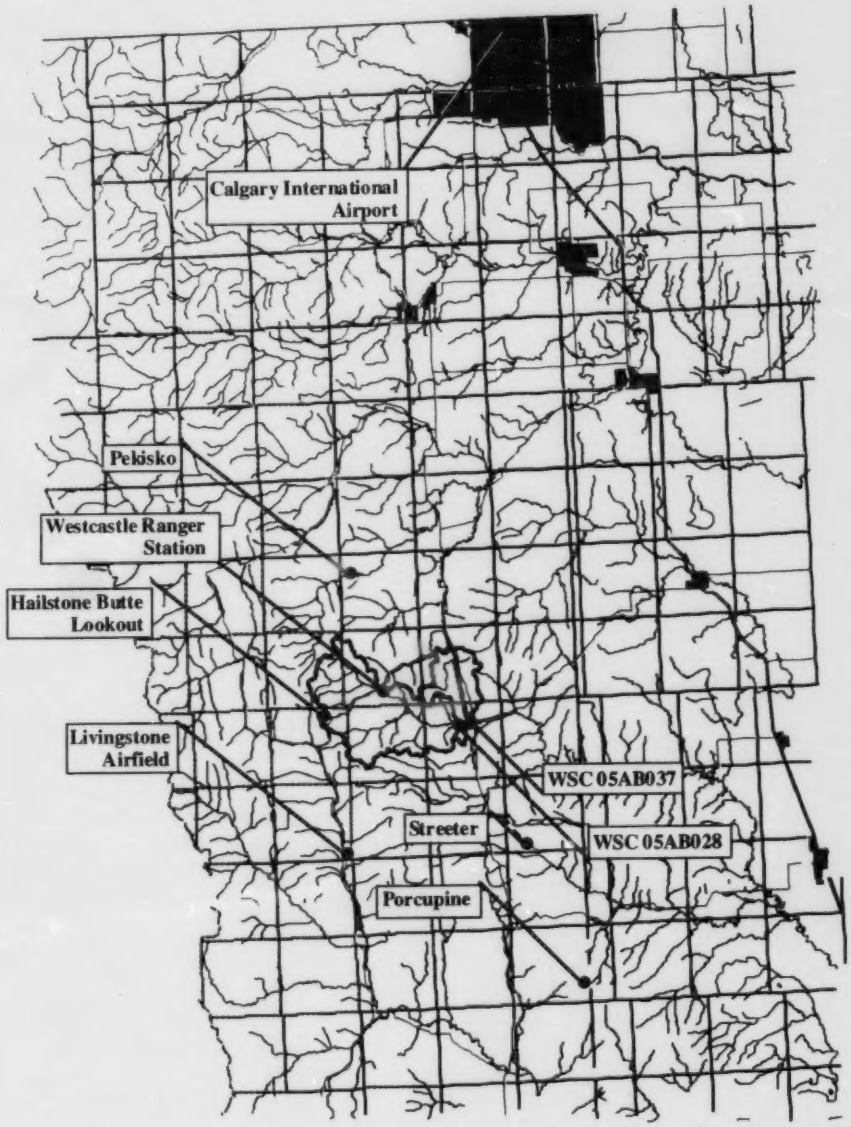



**Figure 4.1: Hydrometric and Meteorological Stations**

4. Refine the presumptive estimates of hydrologic relationships by iteration until acceptable relationships are obtained for all of the sub-basins.

5. The 1975 and 1981 flood events for the basin are two of the top three largest events to occur at Willow Creek near Chain Lakes since the construction of the dam. The 1990 event was included in the analysis as it was the largest event to occur since the expansion of the meteorological network.

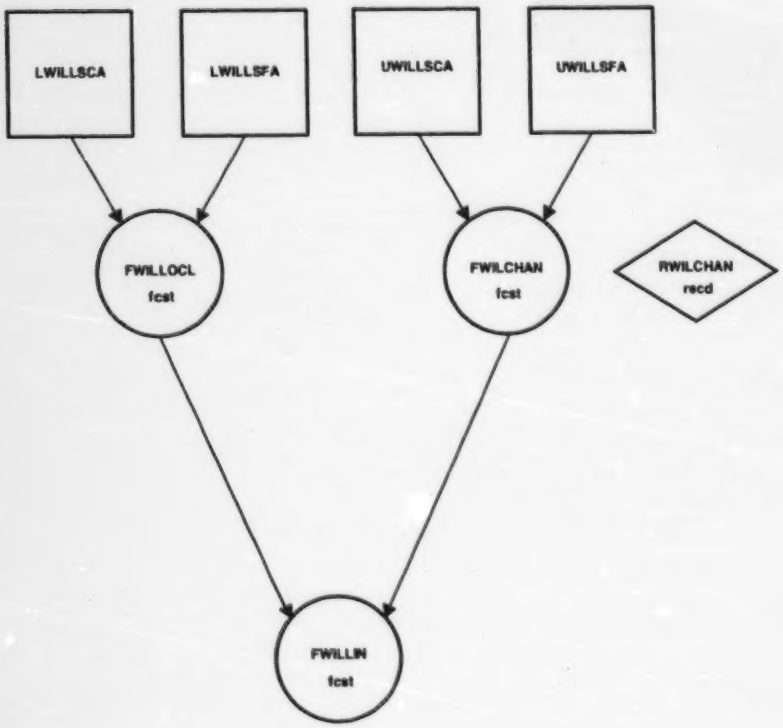



**Figure 4.2: SSARR Model for Willow Creek above Chain Lakes Reservoir**

The final calibrated relationships for the SSARR model sub-basins are provided in Appendix 1.

The simulations for the surface, subsurface and baseflow components are provided for both the snow-covered and snow-free areas of the basin within the SSARR model. The resulting combined hydrographs from each sub-basin are then compared to the recorded data. These graphs are shown in Appendix 2.

# 5.0 GENERATION OF PROBABLE MAXIMUM FLOOD

## 5.1 Critical Shape of Rainfall Mass Curves

To determine the critical timing of the PMP rainfall for input into the SSARR model, preliminary runs are made using a variety of rainfall mass curves. The Chicago distribution was chosen for the initial run. The rainfall mass curve producing the highest runoff response is summarized in Table 5.1. It was concluded during this process that the Willow basin is not very sensitive to the distribution of the precipitation. However, as indicated below, the distribution producing the largest peak has a large proportion of the PMP falling in the latter portion of the event. This level of sensitivity and the atypical distribution can be attributed to the relatively small size of the Willow drainage basin and the associated short time of concentration.

**Table 5.1: Critical Rainfall Mass Curve**

| Hours | 0-6 | 6-12 | 12-18 | 18-24 | 24-30 | 30-36 | 36-42 | 42-48 |
|---|---|---|---|---|---|---|---|---|
| PMP Depth Ranking | 8 | 6 | 5 | 3 | 2 | 1 | 4 | 7 |

## 5.2 PMF Estimates

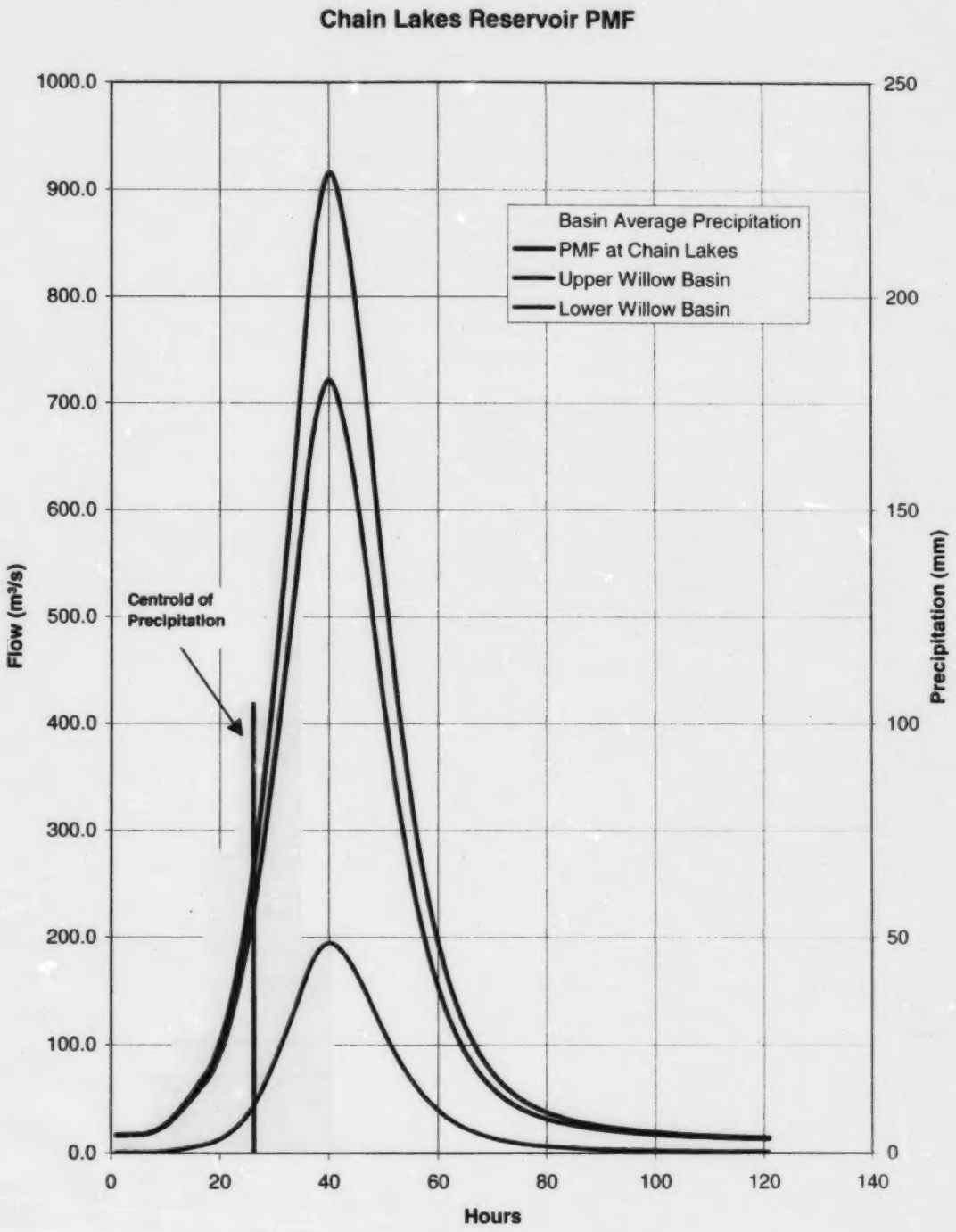
The flood peak results from the SSARR model analyses are provided in Table 5.2. The corresponding hydrograph is shown in Figure 5.1. The complete results of the PMF SSARR run are available in Appendix 3.

**Table 5.2: Breakdown of Sub-Basin Hydrographs**

| SSARR Model Area | Peak Flow $m^3/s$ | Time to Peak hours [1] | Peak Yield $m^3/s/km^2$ | Peak Yield $cfs/mi^2$ |
|---|---|---|---|---|
| Upper Willow | 721 | 11 | 4.44 | 407 |
| Lower Willow | 194 | 11 | 4.09 | 376 |
| Total Basin | 916 | 11 | 4.36 | 399 |

1. Time to peak is from center of mass of PMP – the center of mass being 29 hours into the 48-hour event.

**Figure 5.1: PMF Hydrograph**



# 6.0 PMF COMPARISON AND DISCUSSION

## 6.1 Comparison with Previous Studies

The present estimate of the PMF hydrograph for the Chain Lakes Reservoir is more than double that estimated in the 1979 report (Reference 5) and 11% larger than that presented in the 1983 report which used the same SNBB procedure (Reference 6). A comparison of PMF estimates at the Chain Lakes Reservoir is presented in Table 6.1. As the 1986 study did not produce an estimate at the reservoir it cannot be included in this comparison.

**Table 6.1: Comparison of 1979, 1983 and Recalculated PMF for the Chain Lakes Reservoir**

| PMF | Precip mm | Peak Flow $m^3/s$ | Time to Peak hours | Peak Yield $m^3/s/km^2$ |
|---|---|---|---|---|
| 1999-2000 Study | 420 | 916 | 11[1] | 4.36 |
| 1983 Study | N/A | 820 | N/A | 3.90 |
| 1979 Study | N/A | 425 | N/A | 2.03 |

1. Time to peak is from center of mass of PMP – the centroid being 29 hours into the 48 hr event

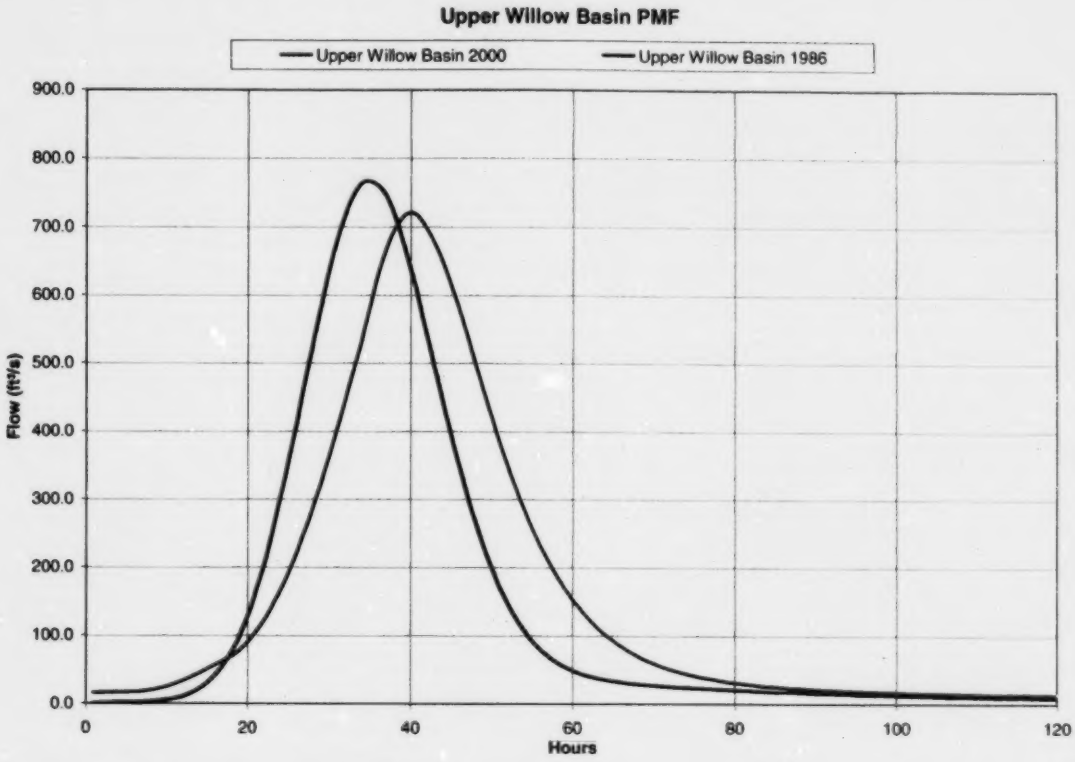
The present estimate of the PMF hydrograph at the WSC gauge Willow Creek above Chain Lakes does not differ significantly from the PMF hydrograph estimated during the 1986 AENV PMF analysis. A hydrograph for the Chain Lakes Reservoir was not included as part of the 1986 study. A comparison between the old and new PMF hydrographs at the gauge are shown in Figure 6.1 and Table 6.2 summarizes the differences in the flood hydrograph characteristics.

**Table 6.2: Comparison of 1986 PMF at WSC Gauge 05AB028 and Recalculated PMF at WSC Gauge 05AB028**

| PMF | Precip mm | Peak Flow $m^3/s$ | Time to Peak hours | Peak Yield $m^3/s/km^2$ |
|---|---|---|---|---|
| 1999-2000 Study | 420 | 721 | 11[1] | 4.44 |
| 1986 AENV Study | 442 | 760 | 19[2] | 4.69 |

1. Time to peak is from center of mass of PMP – the centroid being 29 hours into the 48 hr event
2. Time to peak is from center of mass of PMP – the centroid being 20 hours into the 48 hr event

**Figure 6.1: PMF Hydrograph Comparison**




## 6.2 Justification of Calculated PMF

The differences between the 1979/1983 PMF estimates and the present can be attributed to the two different methods used to complete the analysis. The two previous analyses were completed using the SNBB procedures for prairie provinces while the current analysis used the WMO guidelines to determine the PMP and the SSARR model to estimate the PMF. The procedures used to estimate the PMF hydrograph for the Chain Lakes Reservoir are similar for both the present and the 1986 studies.

The decrease in the PMP between the 1986 and 2000 studies is in the order of magnitude of 2.5%. This difference in the PMP is due in part to the current study having a finer resolution of the orographic precipitation analysis. The 5.6% decrease in the PMF hydrograph estimate is due to the lower PMP value as well as the limited data available for the calibration of the SSARR watershed model in 1986. Appendix 1 presents the SSARR model and basin relationships. The calibration results are presented in Appendix 2.

## 6.3 Comparison of PMF Values in Neighbouring Basins

Alberta Environment has undertaken several PMF studies. These include the PMF for the Dickson Dam, Waterton Reservoir, Oldman Reservoir, Milk River Dam as well as the Willow Creek basin near Claresholm. Table 6.3 summarizes the PMF information for the above sites and provides a comparison to the PMF at the Chain Lakes Reservoir. The table shows that the unit yield and runoff volume for the PMF at Chain Lakes Reservoir is reasonable when compared with other estimates given the relative size of its drainage basin.

**Table 6.3: PMF Flood Characteristics for Nearby Watersheds**

| PMF Location | Area ($km^2$) | Precip (mm) | Qp ($m^3/s$) | Qp ($m^3/s/km^2$) | Runoff (mm) | % Runoff |
|---|---|---|---|---|---|---|
| Willow Creek near Claresholm | 1116 | 362 | 2710 | 2.43 | 281 | 77.6 |
| Waterton Reservoir | 1263 | 389 | 2340 | 1.85 | 329 | 84.5 |
| Milk River Dam | 2510 | 361 | 4450 | 1.77 | 214 | 59.2 |
| Oldman Dam | 4374 | 338 | 9460 | 2.16 | 326 | 96.4 [1] |
| Dickson Dam | 5567 | 321 | 11460 | 2.06 | 280 | 87.2 |
| Chain Lakes Reservoir | 210 | 420 | 916 | 4.36 | 359 | 85.5 |

1. Includes volume from snowmelt

## 6.4 Comparison with Recorded Floods

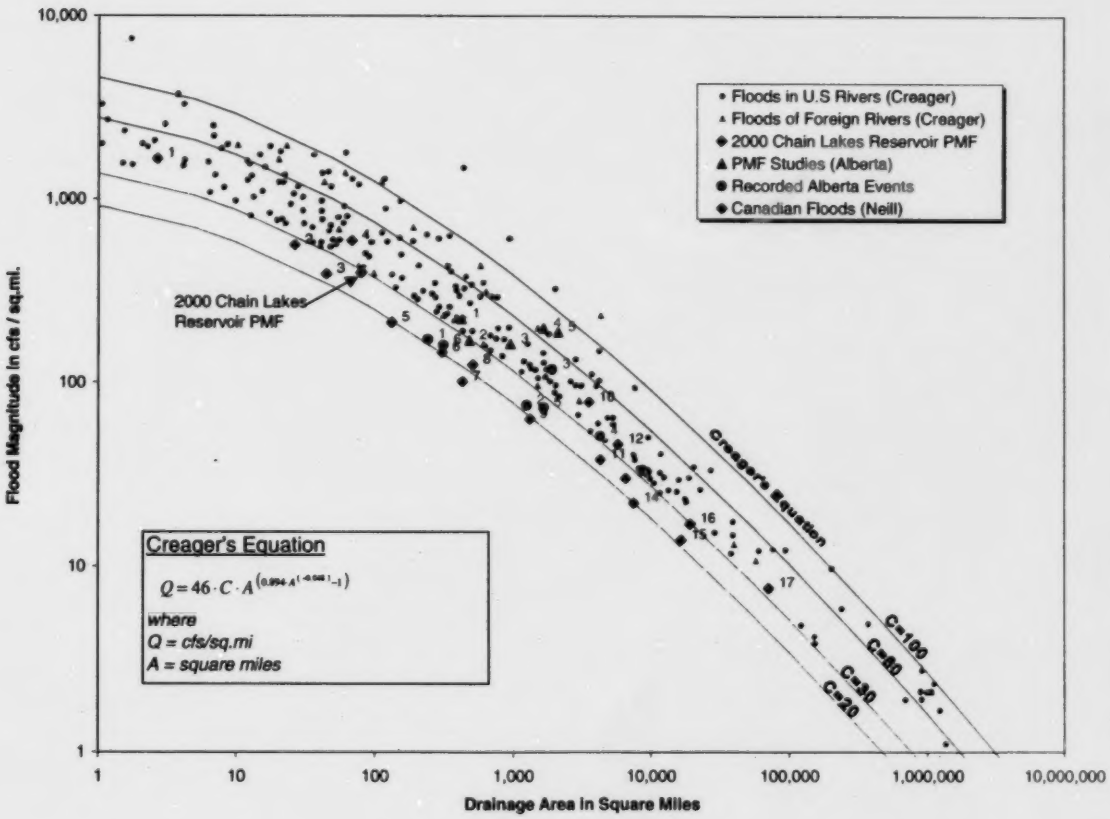
Flood envelope curves, a plot of unit area discharge versus contributing area, provide a visual means of comparing the peak flow rate of the Chain Lakes Reservoir PMF to observed flood events and to other PMF flood studies. The Creager Diagram, shown in Figure 6.2, documents many such floods. Figure 6.2 compares the relative magnitude of the 2000 PMF estimate for the Chain Lakes Reservoir with other theoretical and recorded flood events. These events have been itemized in Table 6.4. Table 6.4 provides peak flow yields for recorded Canadian floods and for Alberta PMF studies. Comparison of peak flow yields between Alberta conditions and national or even international conditions should be undertaken with caution because hydrometeorologic conditions may be extremely variable from region to region. Reference 4 describes the use of the diagram, and provides some additional Canadian data.

## Table 6.4: Theoretical and Recorded Events Superimposed on Creager Diagram

| Flood Category | Drainage Area (sq.mi.) | Yield (cfs/sq.mi.) |
|---|---|---|
| **Canadian Floods (Neill)** | | |
| 1 Harvey Cr. BC, 1969 | 3 | 1660 |
| 2 Rainy R. at the mouth BC, 1958 | 27 | 564 |
| 3 Norris Cr. near Dewdney BC, 1984 | 45 | 391 |
| 4 Zeballos R. near Zeballos BC, 1975 | 69 | 596 |
| 5 Hirsch Cr. near the mouth BC, 1974 | 134 | 213 |
| 6 Humber R. at Weston ON, 1954 | 309 | 146 |
| 7 Castle R. at Cowley AB, 1923 | 435 | 101 |
| 8 Bay du Nord R. at Big Falls NF, 1983 | 517 | 125 |
| 9 Exploits R. below Stoney Brook NF, 1983 | 1340 | 63 |
| 10 Iskut R. Below Jonson R. BC, 1961 | 3610 | 78 |
| 11 Wapiti R. near Grande Prairie AB, 1972 | 4360 | 38 |
| 12 Arctic Red R. at Martin House NWT, 1970 | 5840 | 46 |
| 13 Oldman R.at Lethbridge AB, 1908 | 6640 | 30 |
| 14 Muskwa R. near Fort Nelson BC, 1971 | 7606 | 22 |
| 15 Fort Nelson R. near Fort Nelson BC, 1971 | 16800 | 14 |
| 16 Smoky R. at Watino AB, 1972 | 19400 | 17 |
| 17 Peace R. at Peace River AB, 1965 | 72000 | 7.6 |

| Flood Category | Drainage Area (sq.mi.) | Yield (cfs/sq.mi.) |
|---|---|---|
| **Recorded Alberta Events** | | |
| 1 Deep Valley Cr. Near Valleyview, 1987 | 245 | 172 |
| 2 Kakwa R. near Grande Prairie, 1982 | 1275 | 75 |
| 3 Simonette R. near Goodwin, 1987 | 1951 | 118 |
| 4 Wapiti R. near Grand Prairie, 1982 | 4360 | 51 |
| 5 Oldman R. at Oldman Dam, 1995 | 1698 | 73 |
| 6 Castle R. near Beaver Mines 1995 | 317 | 160 |
| **PMF Studies (Alberta)** | | |
| 1 Willow Cr. near Claresholm | 431 | 222 |
| 2 Wateron R. at Waterton Reservoir | 488 | 169 |
| 3 Milk R. at Milk R. Dam | 970 | 162 |
| 4 Oldman R. at Oldman Dam | 1690 | 198 |
| 5 Red Deer R. at Dickson Dam | 2150 | 188 |
| **2000 Chain Lakes Reservoir PMF** | | |
| 1 Chain Lakes PMF | 81 | 399 |

## Figure 6.2: Flood Events and PMF Events Superimposed on Creager's Plot



# 7.0 SUMMARY AND CONCLUSIONS

The purpose of this study was to update the Probable Maximum Flood estimate for the Chain Lakes Reservoir.

In this study, the probable maximum precipitation is derived on the basis of the World Meteorological Organization (WMO) guidelines. The orographic separation procedure is used, which takes into account the two precipitation producing mechanisms present in the study basin. These are the lifting of air due to ground slopes, termed orographic precipitation, and the lifting of air due to meteorological processes, termed convergence precipitation.

The average 48-hour PMP for the watershed upstream of the Chain Lakes Reservoir was calculated to be 420 mm. This value compares favourably to PMP estimates for similar east-slope areas in Alberta.

A SSARR model of the basin, calibrated to observed extreme rainfall/runoff events, is used to route the PMP off the watershed and to provide the PMF at the Chain Lakes Reservoir. The resulting hydrograph has a peak discharge of 916 $m^3/s$, and a 120-hour hydrograph volume of 86,230 $dam^3$. The computed runoff volume can be broken down as shown in the following table:

**Table 7.1: Breakdown of Total Runoff**

| Type of Runoff | 120-hour Runoff Volume (mm) | 120-hour Runoff Volume ($dam^3$) | Percent of Precipitation |
|---|---|---|---|
| **Runoff from Snowmelt** | 24 | 4945 | N/A |
| **Runoff from Precipitation** | 359 | 75397 | 85.5% |
| **Total Runoff** | 383 | 80342 | N/A |

Climate change scenarios have not been factored into this report. At this point in time, climate change and its' potential impact on PMP and on PMF estimates are not well understood. The hydrology design component of the structure will continue to be reviewed as part of the ongoing five-year reviews. The need to update the PMF estimates to include climate change at this time is not warranted.

Outlet design changes may be required as a result of the revised PMF estimate contained in this report. Flexibility should be factored into the redesign of the facility, where feasible, to accommodate the potential impacts to PMF arising from climate change in the future.

# REFERENCES


1. "World Meteorological Organization Procedures for Estimation of Probable Maximum Precipitation", World Meteorological Organization, Operational Hydrology Report No. 1,1973.

2. "Probable Maximum Flood for the Proposed Dam and Diversion Sites in the Willow Creek Basin", by J.H. Taggart, Hydrology Section, Alberta Environmental Protection, 1986.

3. "Program Description and User Manual for Streamflow Synthesis and Reservoir Regulation", U.S. Army Corps of Engineers, North Pacific, Portland, Oregon, 1972.

4. "Unusual Canadian Floods and the Creager Diagram", Charles R. Neill, Northwest Hydraulic Consultants Ltd., Edmonton, 1985.

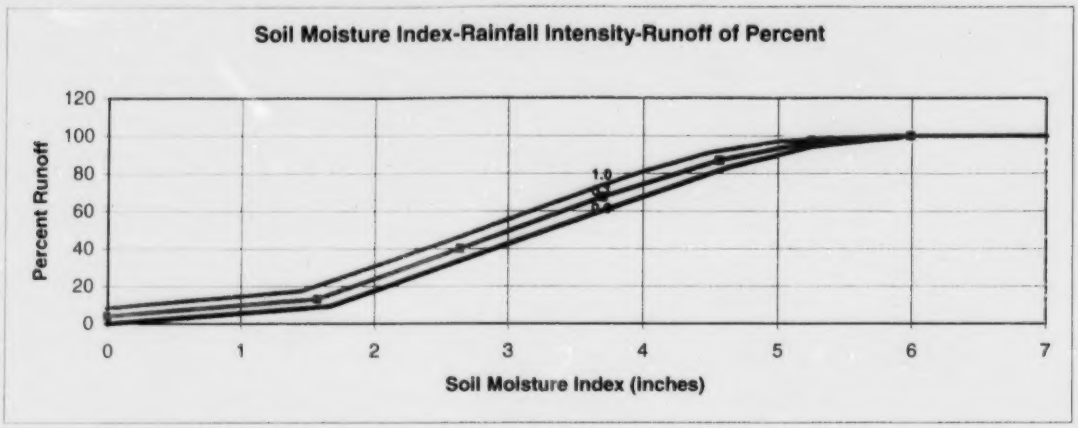
5. "Flood Studies for Major Reservoirs in Southern Alberta, Hydrology Branch Alberta Environment, Edmonton, June 1979.

6. "Inflow Hydrographs for Major Floods at Selected Reservoirs in Alberta", Hydrology Branch Alberta Environment, Edmonton, April 1983.

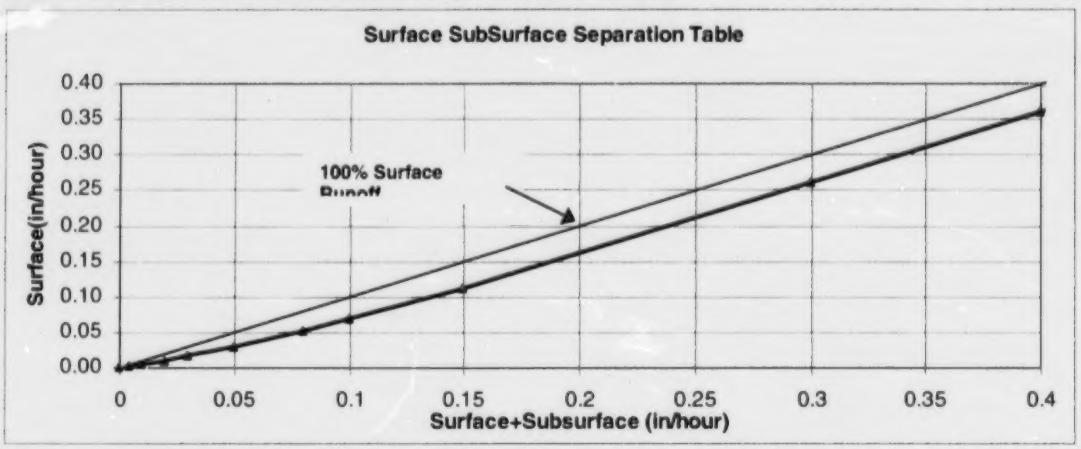
7. "Probable Maximum Flood for the Oldman River Dam", by R.A. Bothe, S.J. Figliuzzi and J.H. Taggart, Hydrology Section, Alberta Environmental Protection, 1985

# APPENDIX 1: SSARR RELATIONSHIPS

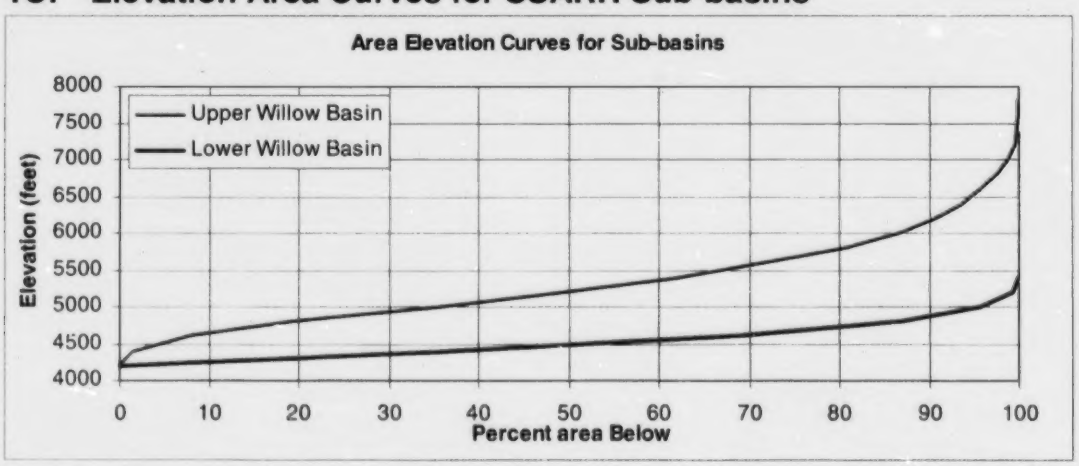
## 1A: Soil Moisture Percent



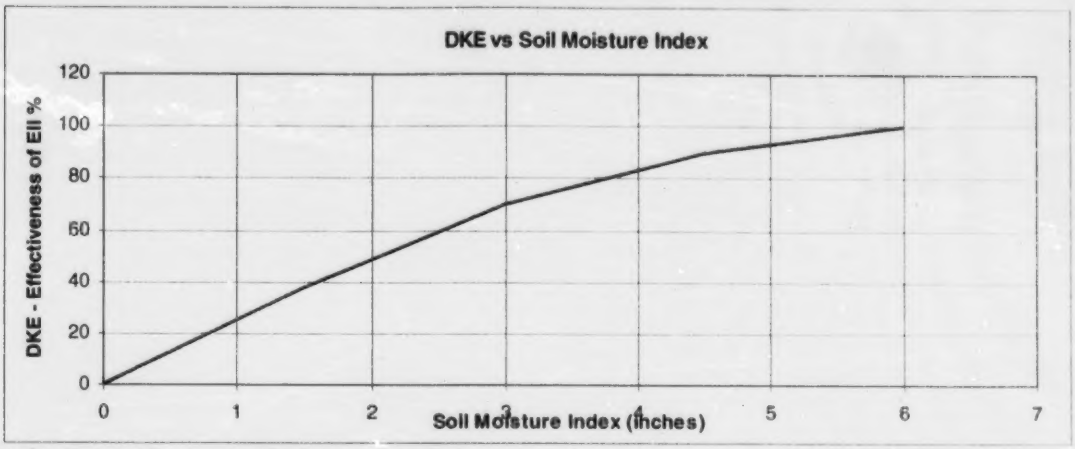

## 1B: Surface-Subsurface Separation Curve



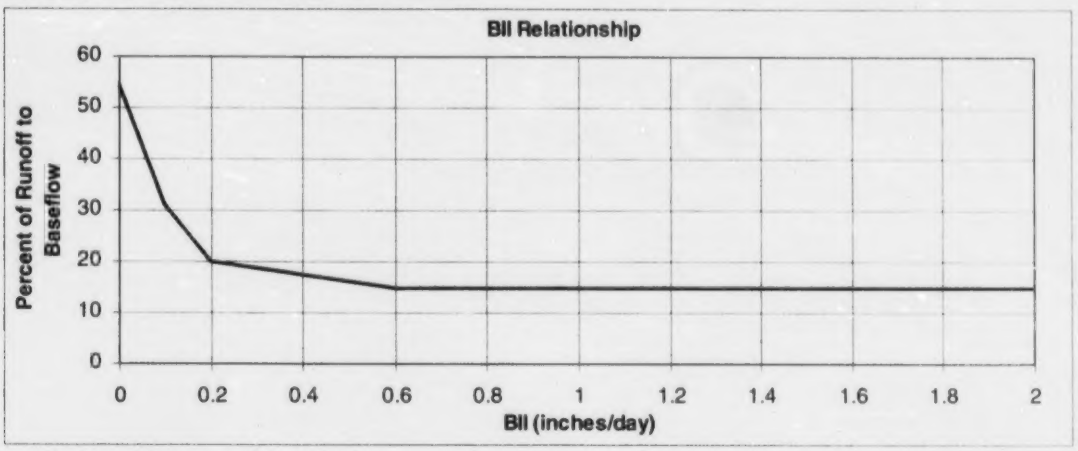

## 1C: Elevation Area Curves for SSARR Sub-basins

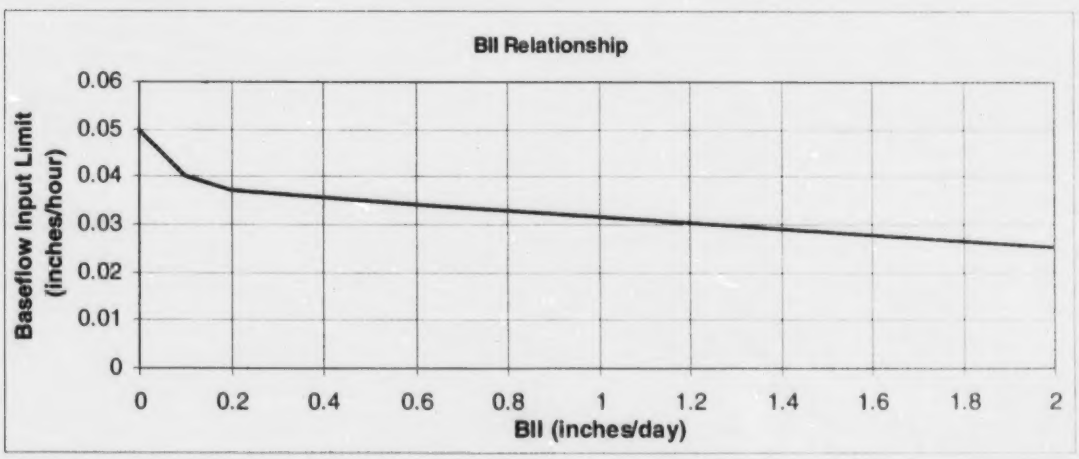


## 1D: Percent Effective ETI Vs Soil Moisture Index

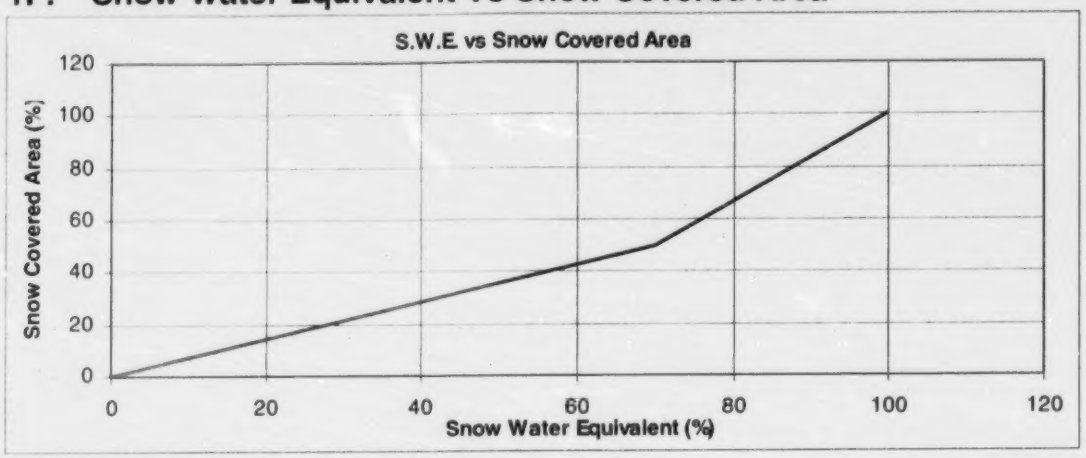



## 1E: Baseflow Infiltration Index

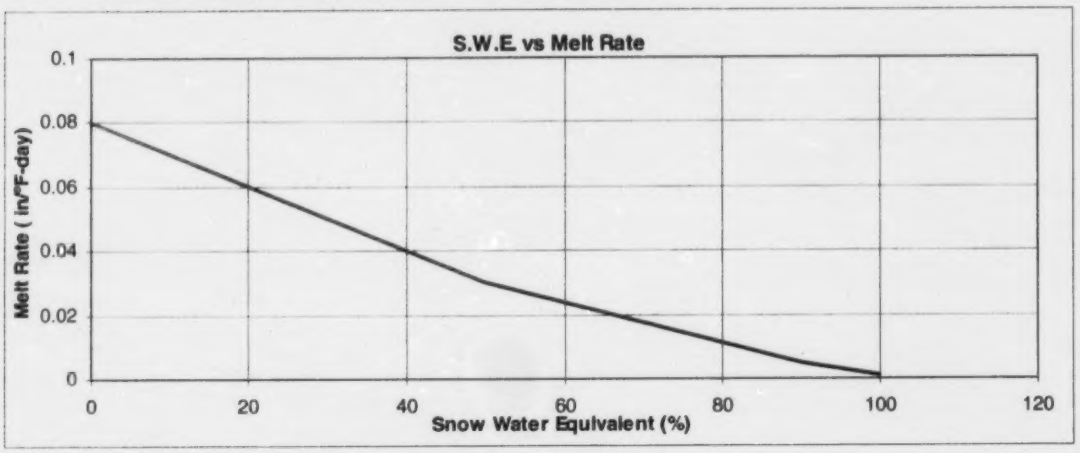


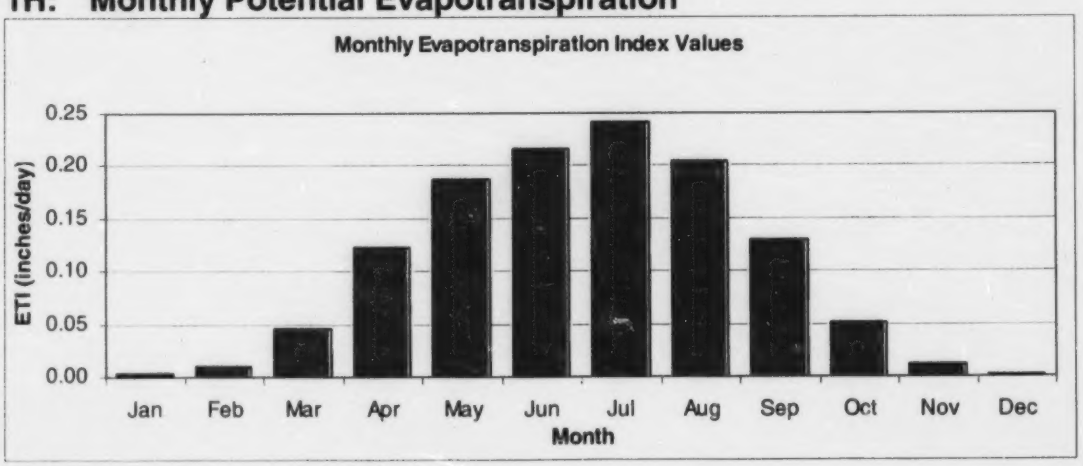
## 1F: Snow Water Equivalent Vs Snow Covered Area




## 1G: Snow Water Equivalent Vs Melt Rate




## 1H: Monthly Potential Evapotranspiration



# 1I: SSARR Model for Inflows to Chain Lakes Reservoir

```
***SSARR MODEL WILLOW CREEK TO CHAIN LAKES - PMF STUDY OCT 2000 REVISED
JOB      1181000 11     1       PMF WILLOW CREEK CALIBRATION


      *** MET STATION IDENTIFICATION - ELEVATION IN FEET ***
CP     AVGP   5036
CP     LOWR   4495
CP     MRUP   6398


      *** SMI-RI-ROP RELATIONSHIPS
CF 1   SML1      .00     0     0  1.67   9.3  2.71    35
CF 2   SML1      .00   3.78    62  4.63    83  5.25    94
CF 3   SML1      .00    6.0   100 99999   100
CF 4   SML1      .10     0     4  1.58  13.1  2.65    40
CF 5   SML1      .10   3.71  67.5  4.57    87  5.26    97
CF 6   SML1      .10    6.0   100 99999   100
CF 7   SML1     2.00     0   8.4  1.48  17.5  2.60    45
CF 8   SML1     2.00   3.68  72.5  4.50    91 5.258  98.5
CF 9   SML1     2.00    6.0   100 99999   100


      *** BII - BFP TABLES ***
CT 1   BI02      3.0     0    55  0.05   .10   .31  0.040
CT 2   BI02      .20    .20 0.037   0.8    15 0.034    2.0
CT 3   BI02       15  0.025 99999    13  .025


      *** DKE FACTOR ***
CT 1   DKE1       2     0     0  1.50   .38   3.0    70
CT 2   DKE1      4.5    90   6.0   100 99999   100


      *** SURFACE - SUBSURFACE SEPERATION TABLES ***
CT 1   SEP1       2     0     0  .005  .0014  .010  .0042
CT 2   SEP1     .020 0.011 0.030 0.019  0.05 0.031  0.08
CT 3   SEP1   0.053   0.1  0.07  0.15 0.113  0.30 0.280
CT 4   SEP1     0.4  0.36  3.00  2.85 99999 99999


      *** S.W.E. VS SNOW COVERED AREA TABLES ***
CT 1   SCA1       2     0     0    70    50   100   100


      *** MONTHLY ETI TABLE ***
CT 1   ETI1       2     1     0     2  0.01     3  0.05
CT 2   ETI1       4    .12     5    19     6   .22     7
CT 3   ETI1      24     8   .20     9   .13    10   .05
CT 4   ETI1      11   .01    12     0


      *** S.W.E. VS MELTRATE TABLES ***
CT 1   MLR4       2     0   .06    50   .03    90   .005
CT 1   MLR4     100  .001 99999 0.001


   ***WATERSHED CHARACTERISTICS
CB 1 UWILLSCA      2       UPPER WILLOW (ABOVE CHAIN LAKES)/SCA
CB 2 UWILLSCA    632  6 4  10 3 110   24 DKE1SCA1WILLETI1SML1
CB 3 UWILLSCA    BI02  200SEP1          060   MLR4       36032 33
CB 4 UWILLSCA    3AVGP100
CB 4 UWILLSCA    4LOWR100
CB 4 UWILLSCA    9MRUP100
C3  UWILLSCA 4200  000 4400  015 4600  080 4800  194 5000  358 5200  495
C3  UWILLSCA 5400  622 5600  722 5800  810 6000  868 6200  907 6400  937
C3  UWILLSCA 6600  958 6800  975 7000  987 7200  995 7400  999999999999


CB 1 UWILLSFA      2       UPPER WILLOW (ABOVE CHAIN LKS)/SFA
CB 2 UWILLSFA    632  6 4  10 3 110   24 DKE1       ETI1SML1
CB 3 UWILLSFA    BI02  200SEP1          060
CB 4 UWILLSFA    2WILL100
CB 4 UWILLSFA    3AVGP100

CB 1 LWILLSCA      2       LOWER WILLOW (LOCAL to RESERVOIR)/SCA
CB 2 LWILLSCA    182  6 4  1003 110   24 DKE1SCA1WIL2ETI1SML1
CB 3 LWILLSCA    BI02  200SEP1          060   MLR4       35532 33
CB 4 LWILLSCA    3AVGP100
CB 4 LWILLSCA    4LOWR100
CB 4 LWILLSCA    9MRUP100
C3  LWILLSCA 4200  000 4400  358 4600  694 4800  872 5000  958 5200  995
C3  LWILLSCA 5400  999999999999


CB 1 LWILLSFA      2       LOWER WILLOW (LOCAL to RESERVOIR)/SFA
CB 2 LWILLSFA    182  6 4  1003 110   24 DKE1       ETI1SML1
CB 3 LWILLSFA    BI02  200SEP1          060
CB 4 LWILLSFA    2WIL2100
CB 4 LWILLSFA    3AVGP100

   ***HYDROMETRIC STATION IDENTIFICATION***
CC 1  FWILLIN            CHAIN LAKES INFLOW - FORECAST
CC 1 FWILCHAN             WILLOW ABOVE CHAIN - FORECAST
CC 1 FWILLOCL             RESERVOIR LOCAL - FORECAST
CC 1 RWILCHAN             WILLOW ABOVE CHAIN - RECORDED


   ***Model Configuration
N    WILLPMF
P    RWILCHAN
P    UWILLSCA  FWILCHAN
P    UWILLSFA  FWILCHAN
P    LWILLSCA  FWILLOCL
P    LWILLSFA  FWILLOCL
P    FWILCHAN  FWILLIN
P    FWILLOCL  FWILLIN
```

# 1J: SSARR Model Data for PMF Inflows to Chain Lakes Reservoir

```
2B00 UWILLSFA 030010675   400 050    0 400     0 0 0
2B 4 UWILLSFA 0300106751  160  160  160  160  160  160  160
160
2B 3 UWILLSFA 0300106751    1    1    1    1    1    1    1    1
2B 2 UWILLSFA 0300106751    1    1    1    1    1    1    1    1

2B00 UWILLSCA 030010675   600 050   1000 600     0 350 350
2B 4 UWILLSCA 0300106751    1    1    1    1    1    1    1
2B 3 UWILLSCA 0300106751    1    1    1    1    1    1    1    1
2B 2 UWILLSCA 0300106751    1    1    1    1    1    1    1    1

2B00 LWILLSFA 030010675   400 050    0 400     0 0 0
2B 4 LWILLSFA 0300106751    0    0    0    0    0    0    0    0
2B 3 LWILLSFA 0300106751    0    0    0    0    0    0    0    0
2B 2 LWILLSFA 0300106751    0    0    0    0    0    0    0    0

2B00 LWILLSCA 030010675   600 050    0 600     0 0 350
2B 4 LWILLSCA 0300106751    0    0    0    0    0    0    0    0
2B 3 LWILLSCA 0300106751    0    0    0    0    0    0    0    0
2B 2 LWILLSCA 0300106751    0    0    0    0    0    0    0    0

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Z403 LOWR,030060675,4,3.5,3.9,6.25,10.65,14,9.85,10.4,5
Z403 LOWR,030070675,4,3.9,3.2,5.3,8.7,11.05,11.85,9.7,6.8
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Z403 LOWR,030110675,4,7.6,4.4,9.1,16.1,18.2,18.05,18.15,12.05
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Z403 LOWR,030130675,4,4.95,6.3,7.3,9.35,11.05,10.9,8.65,7.7
Z403 LOWR,030140675,4,7.55,7.6,8,11.95,14,14.25,12.55,7.2
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Z403 LOWR,030170675,4,4.8,4.85,6.95,9.2,11.3,8.1,9.2,5.25
Z403 LOWR,030180675,4,1.7,1.1,5.65,9.7,12,12.65,12.8,9.05
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Z403 AVGP,030290675,3,0,0,0,0,0,0,0,0
```
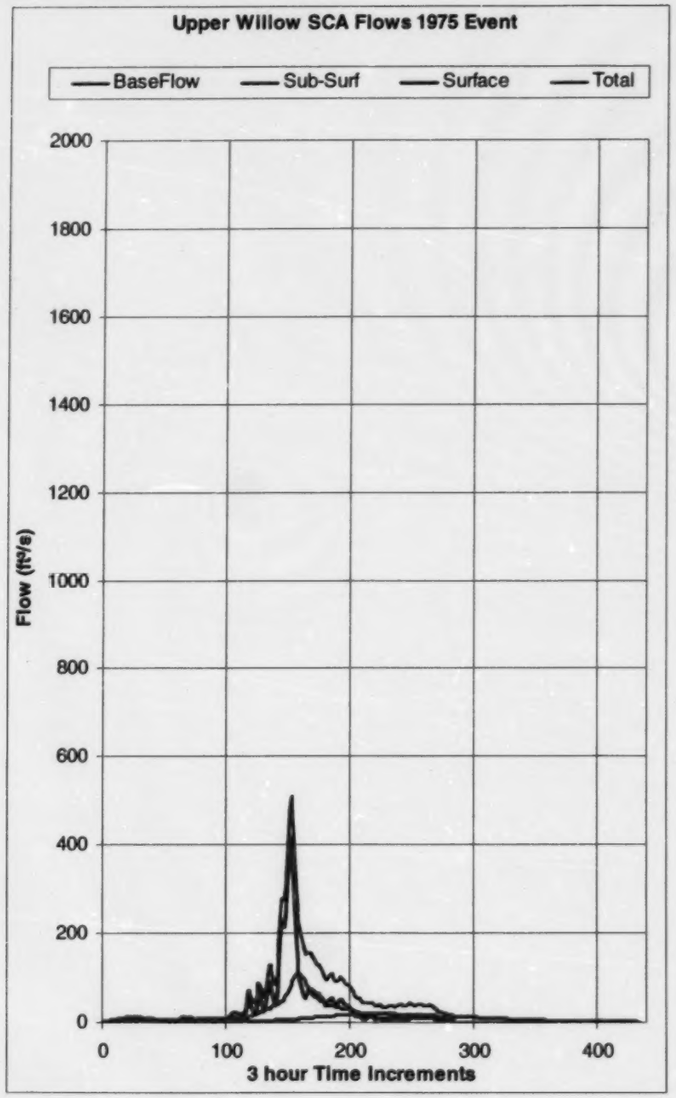
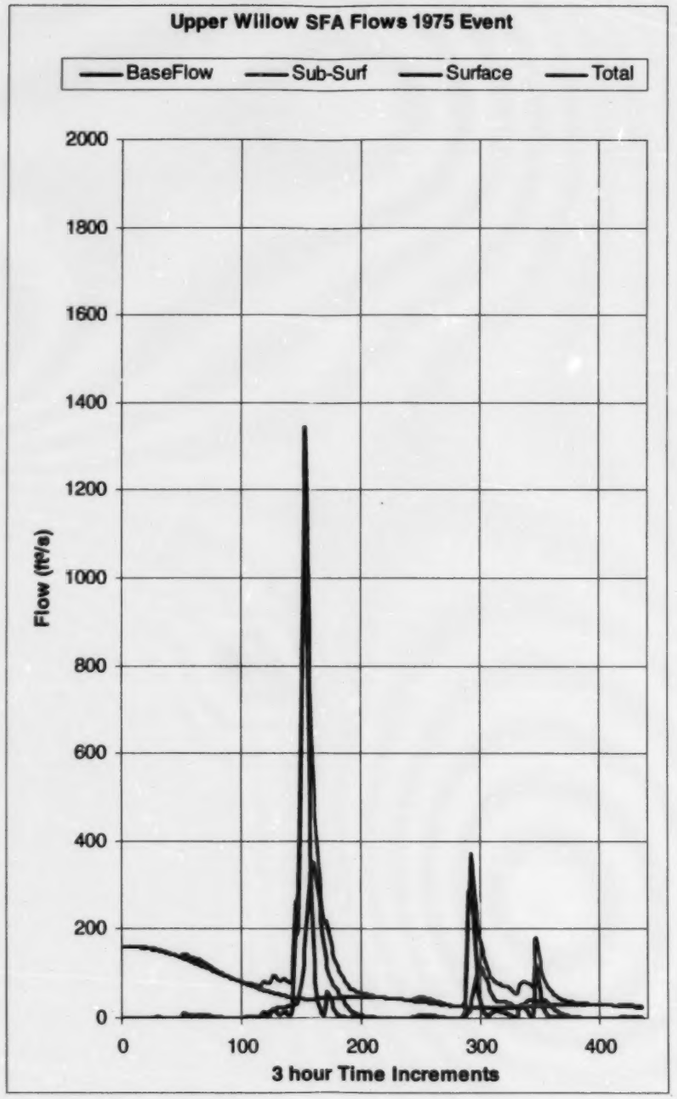
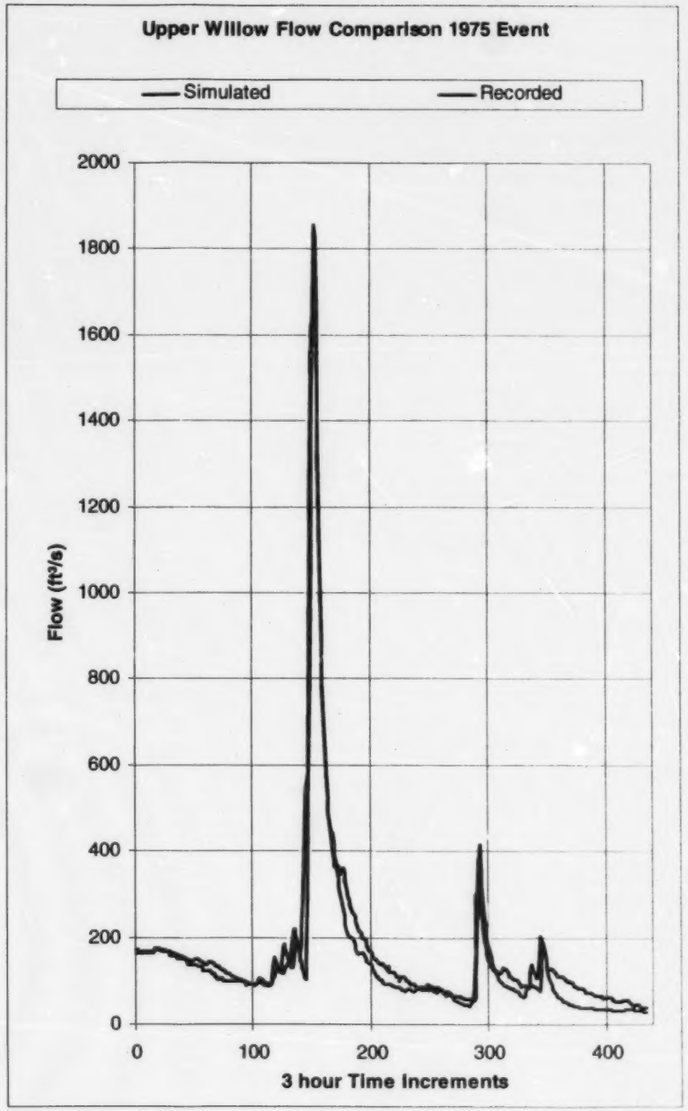

# APPENDIX 2: CALIBRATION RESULTS

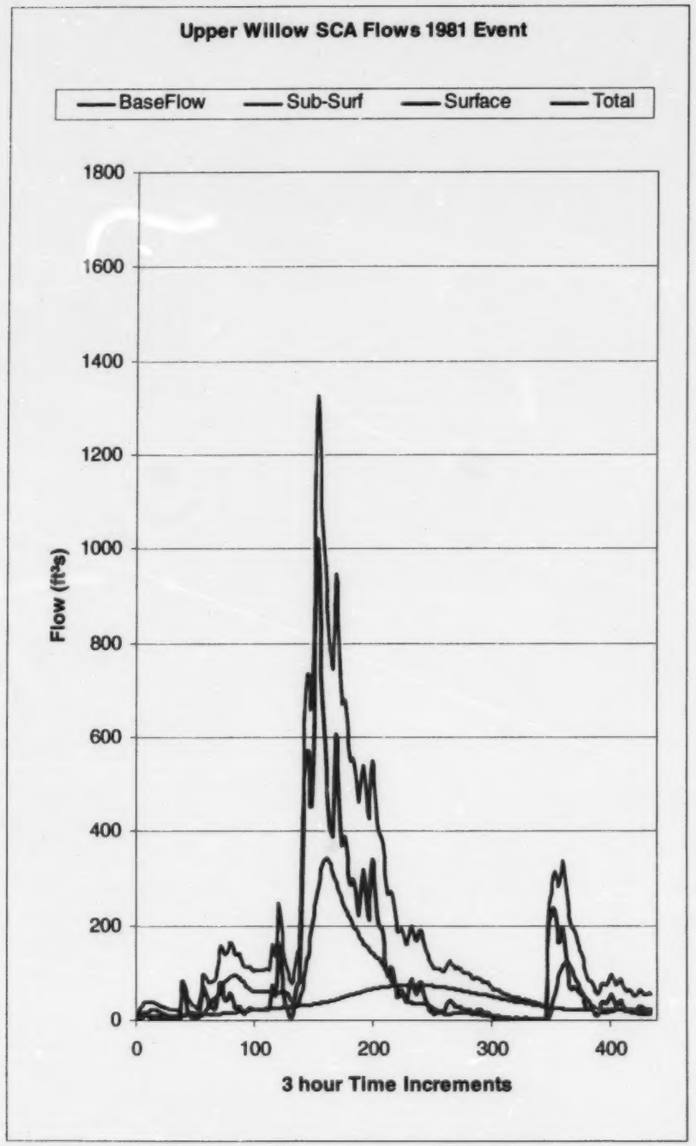
## 2A: Upper Willow Basin

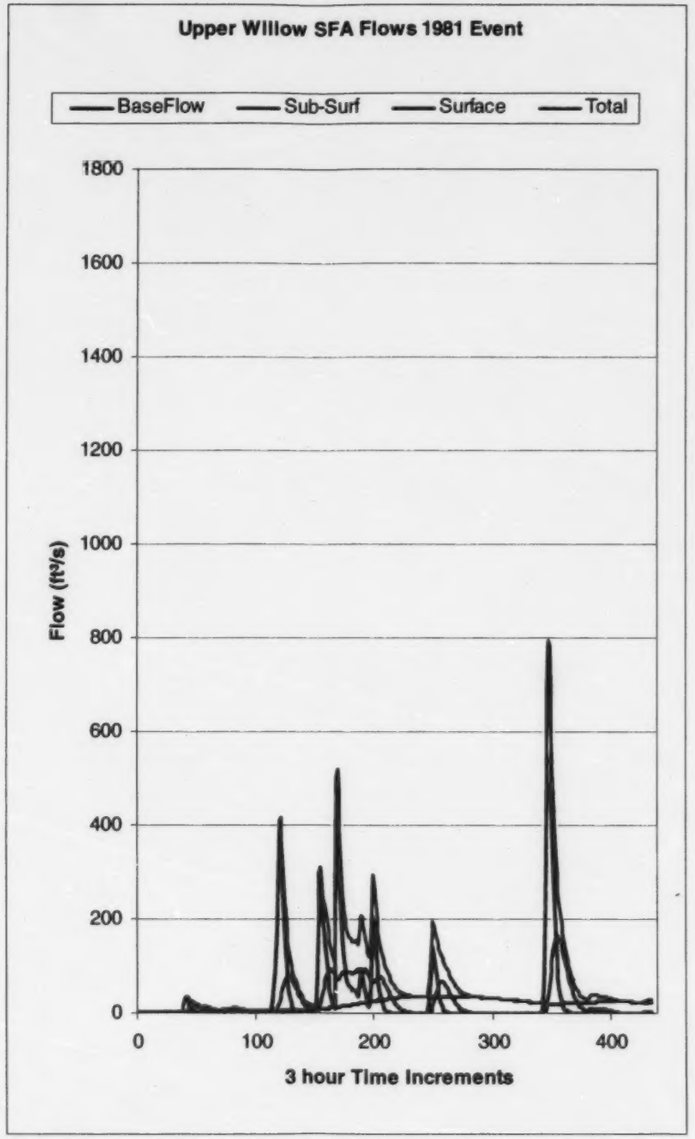


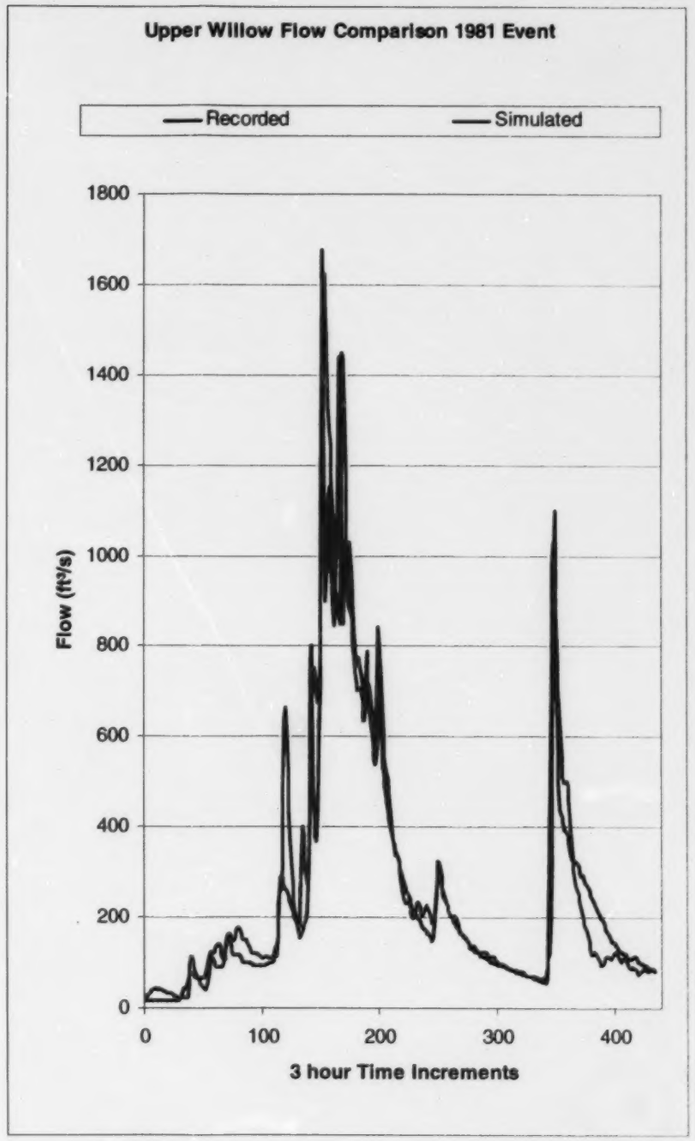



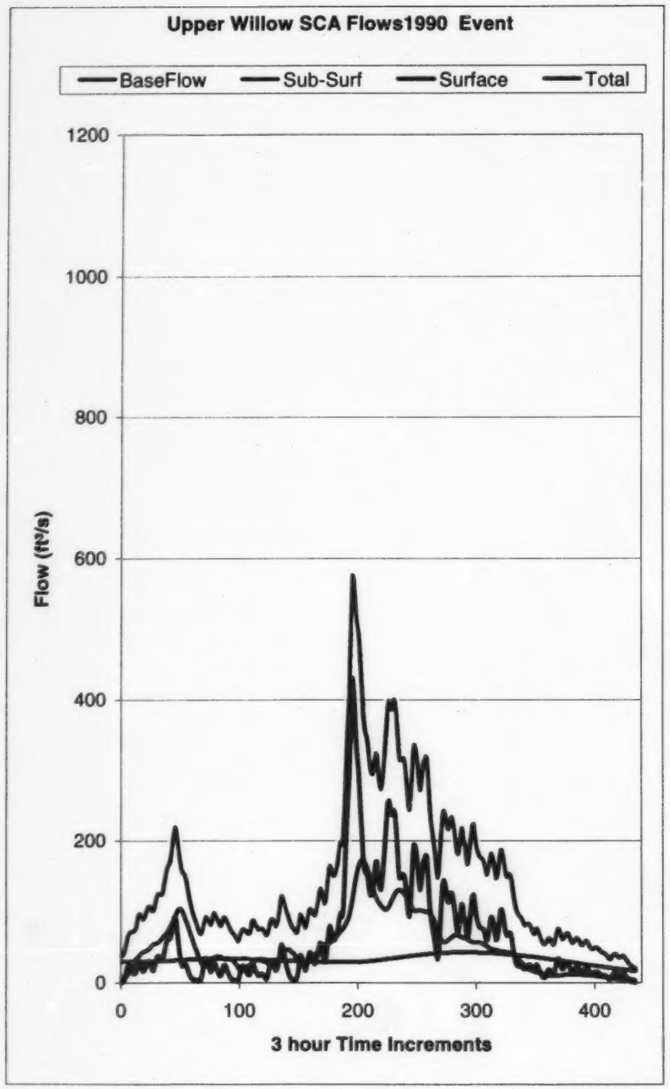

1975 Calibration Period: 01 June 03:00 – 01 August 03:00

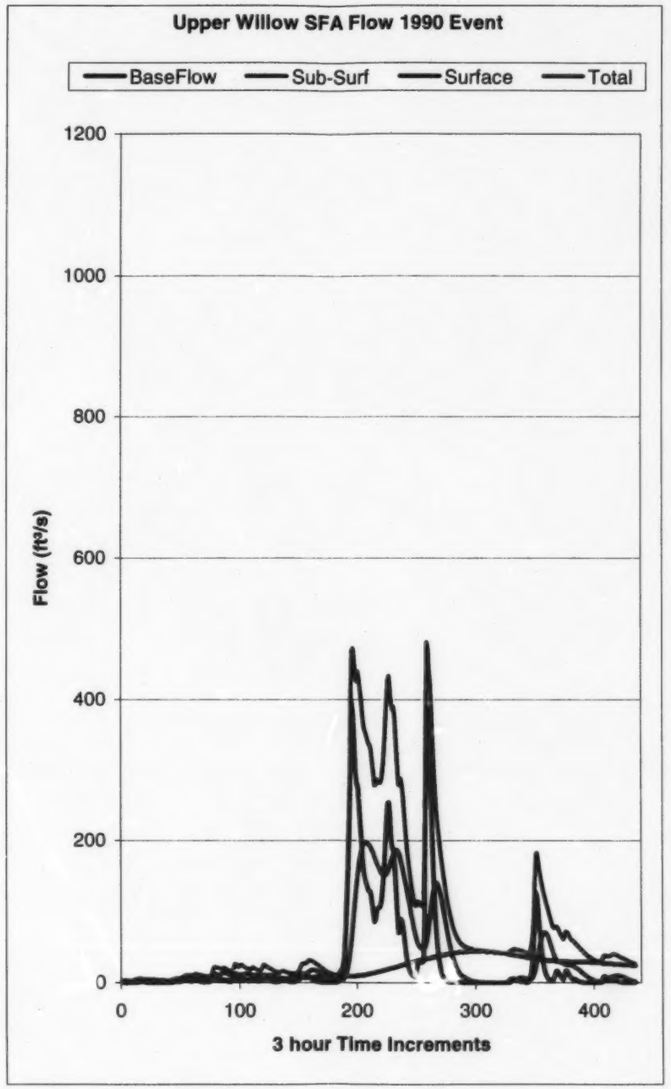


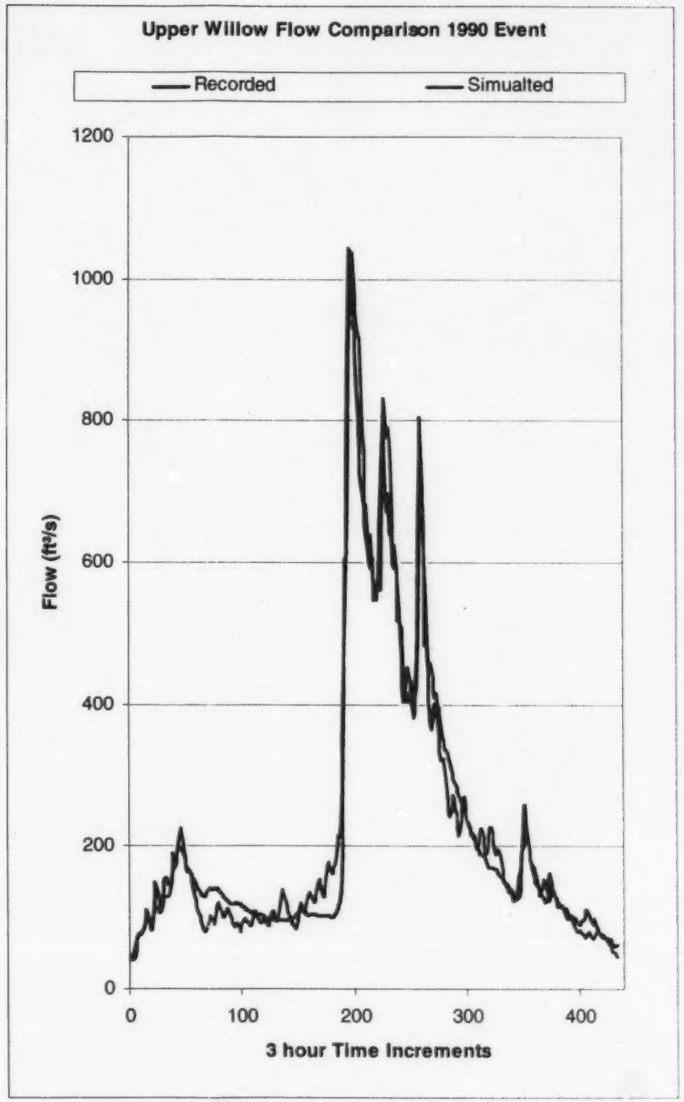




1981 Calibration Period: 01 May 03:00 – 30 July 03:00

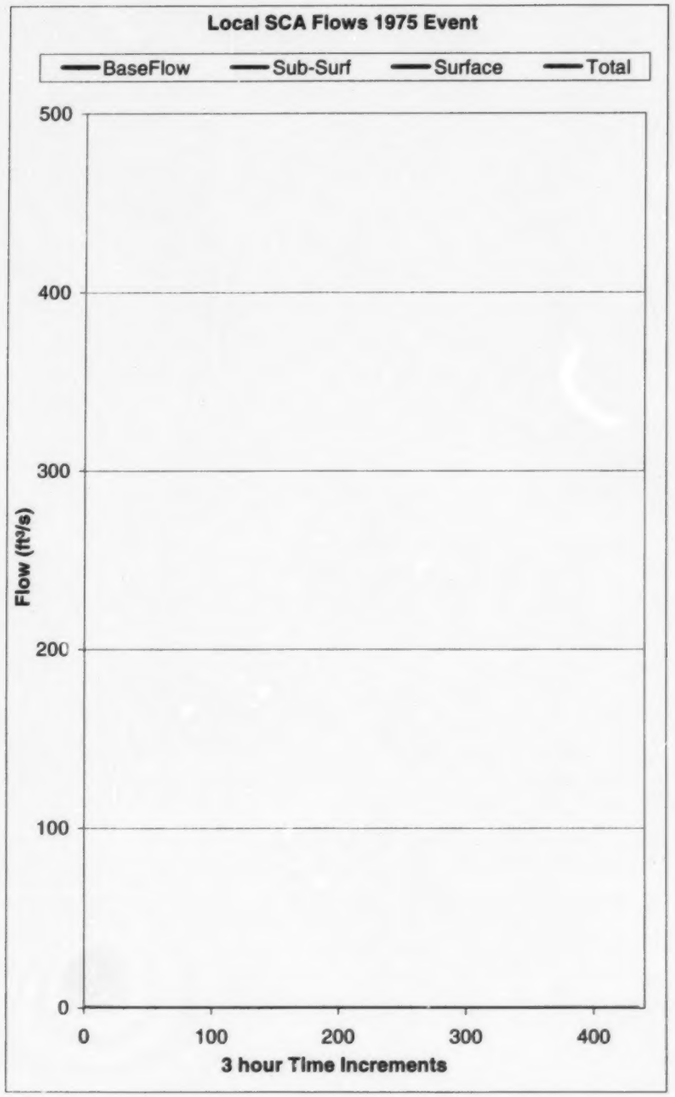


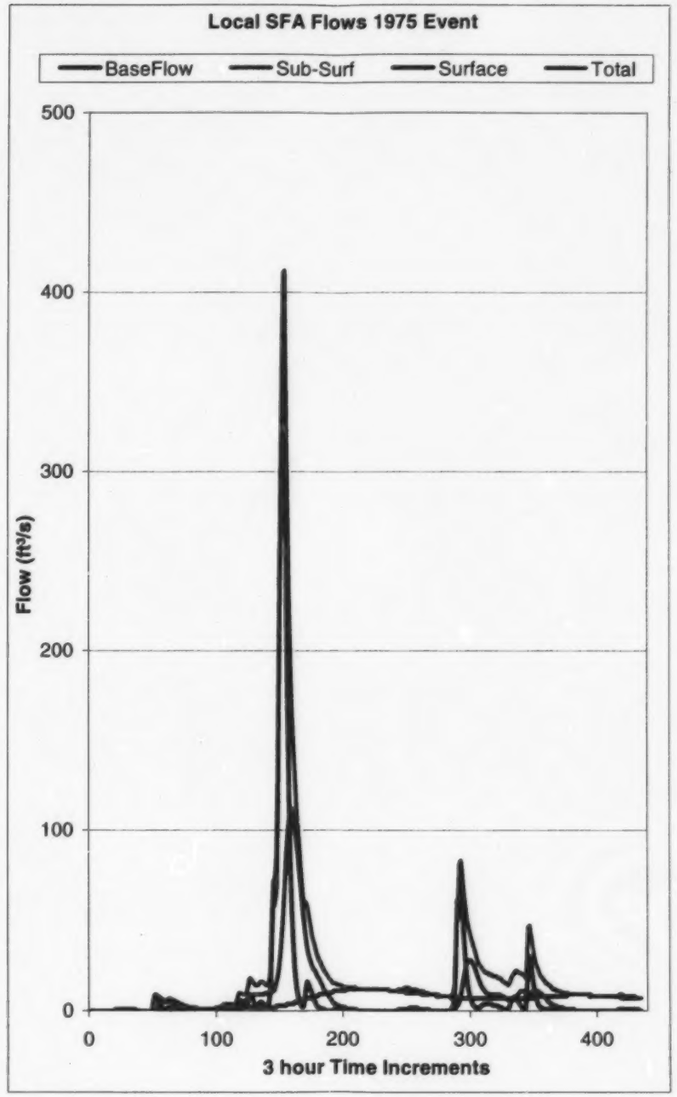



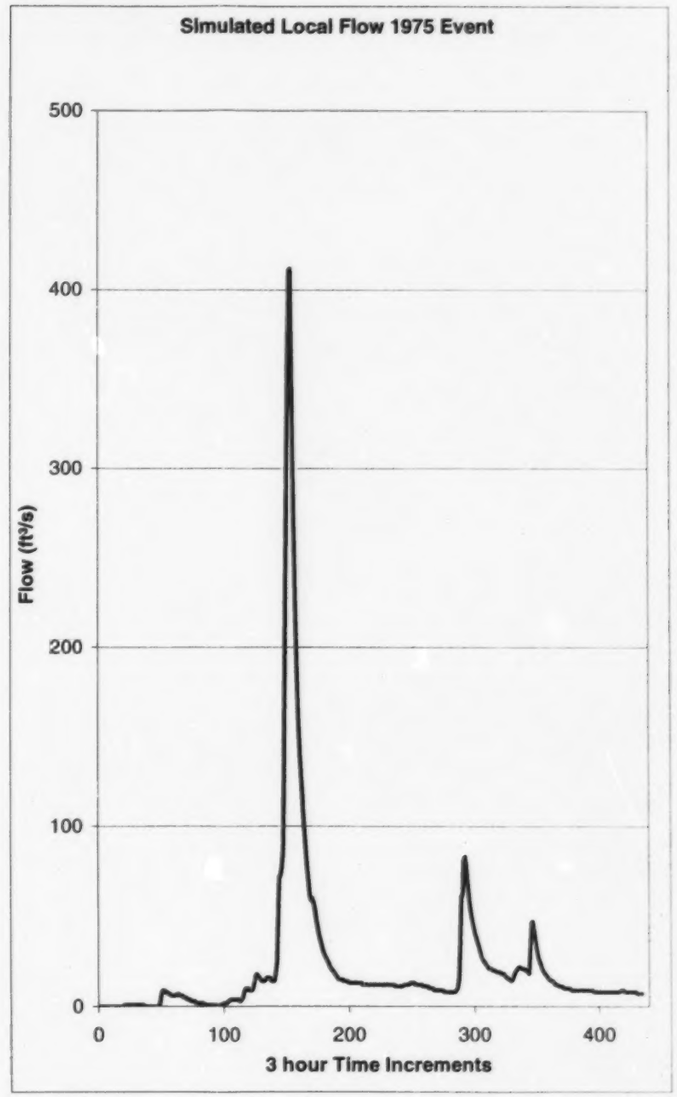




1990 Calibration Period: 01 May 03:00 – 30 June 03:00

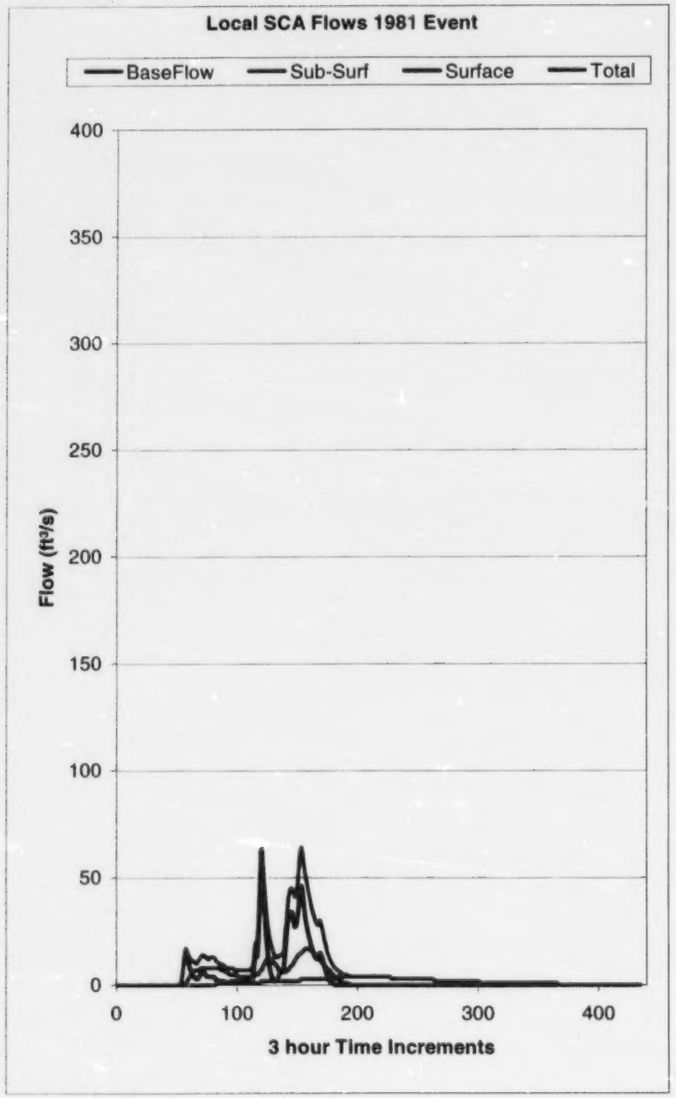
## 2B: Lower Willow Basin

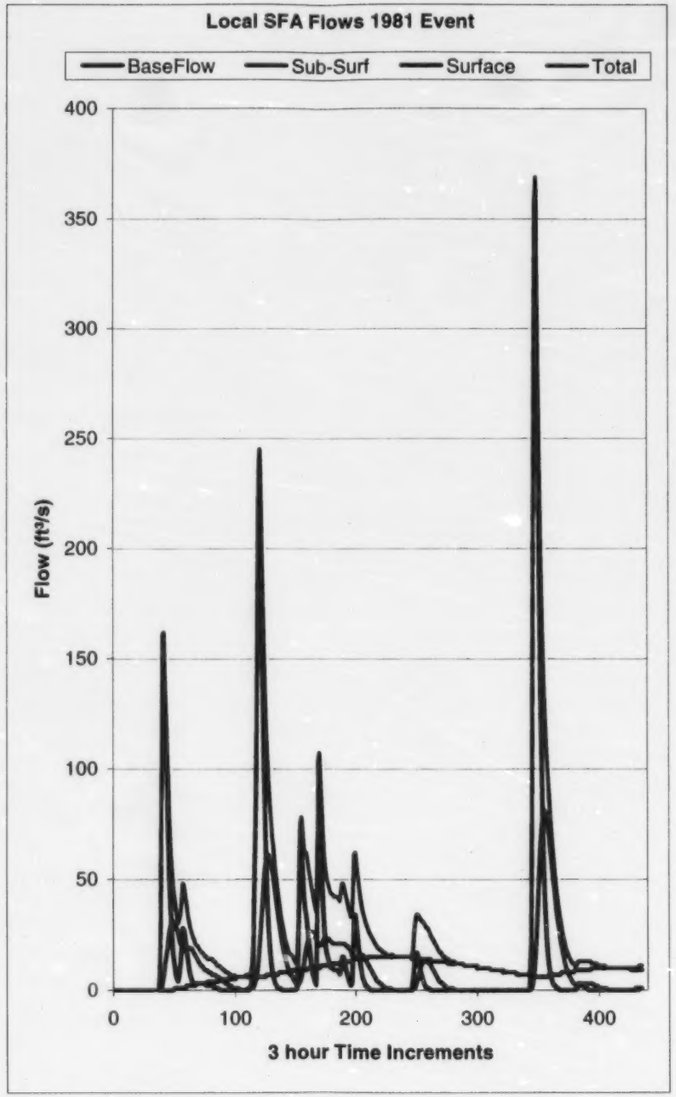


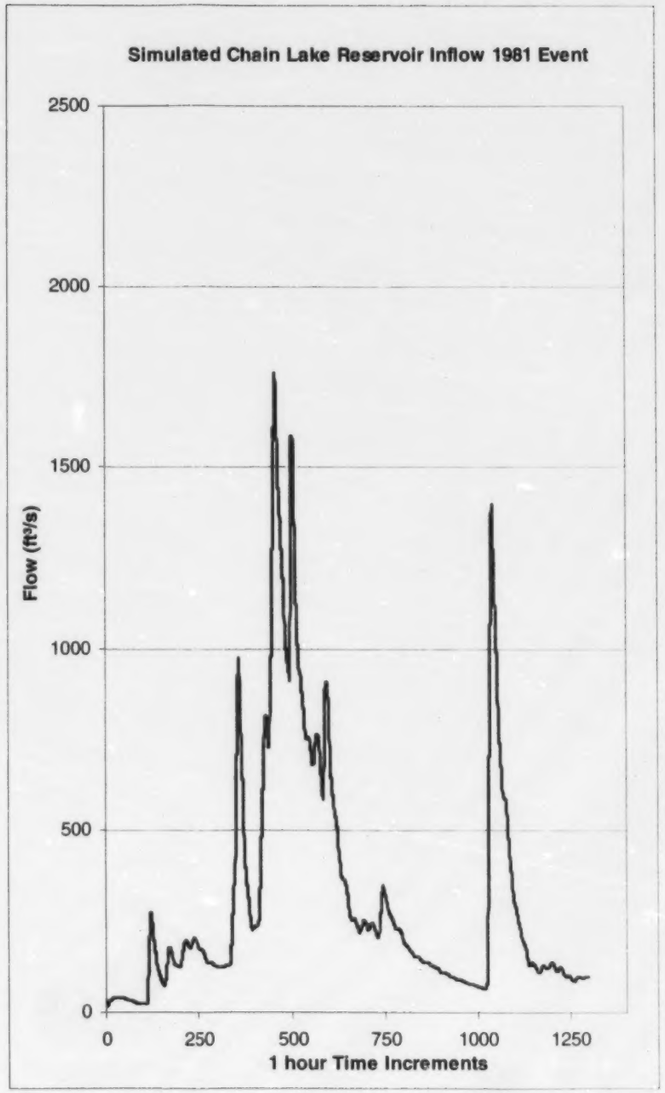



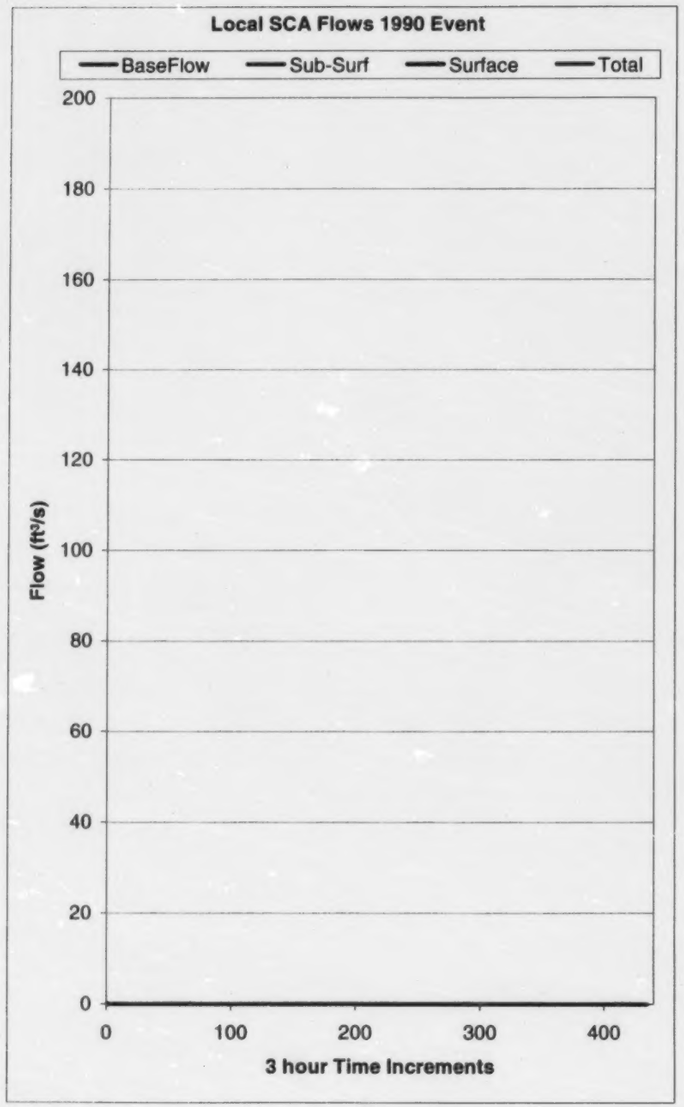

1975 Calibration Period: 01 June 03:00 – 1 August 03:00

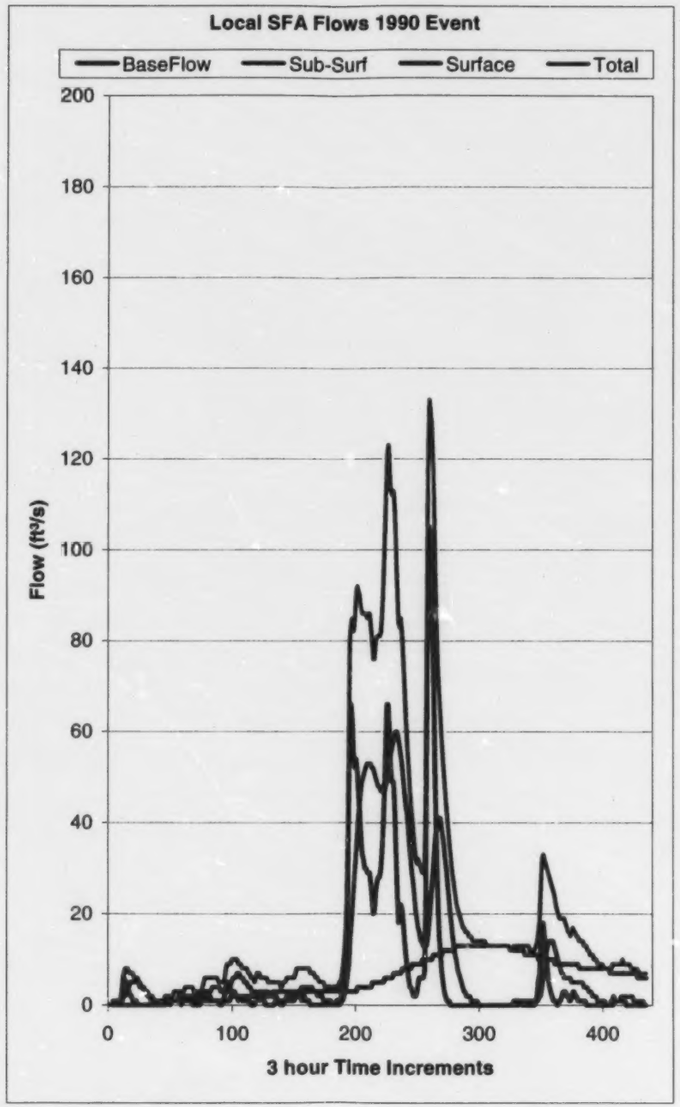


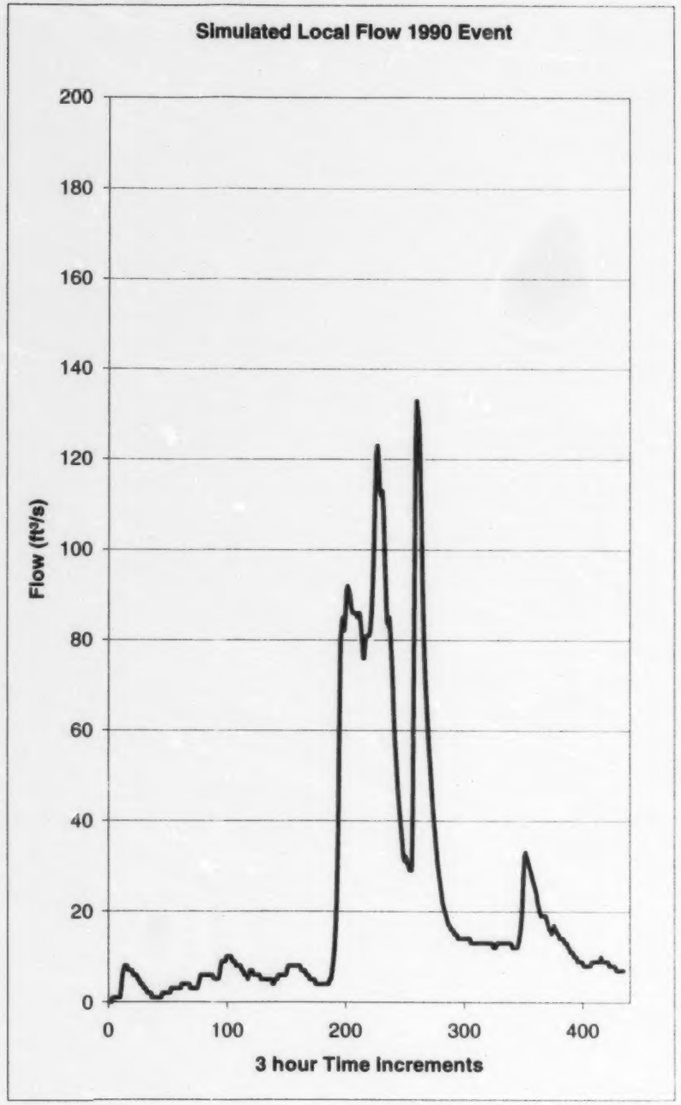




1981 Calibration Period: 01 May 03:00 – 30 July 03:00

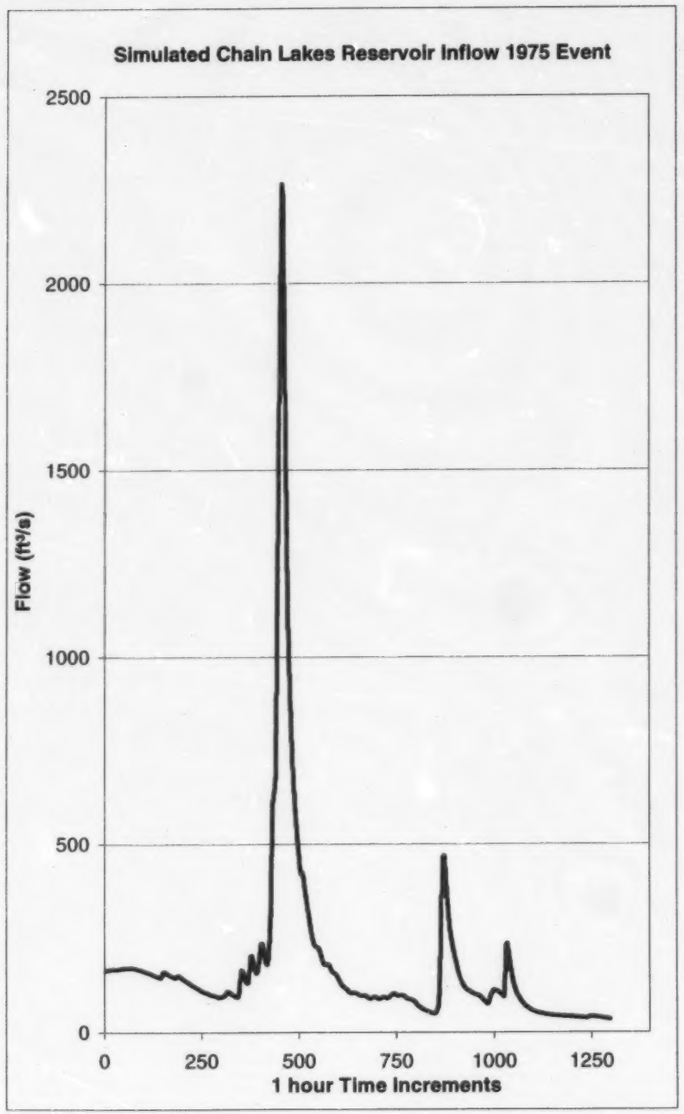


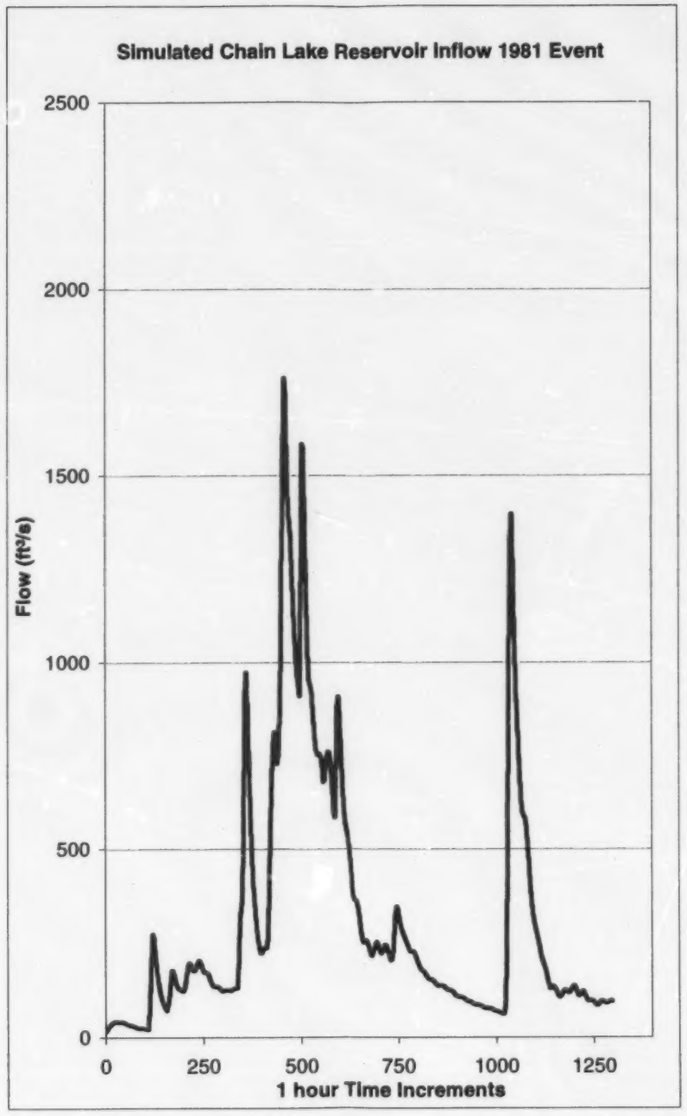



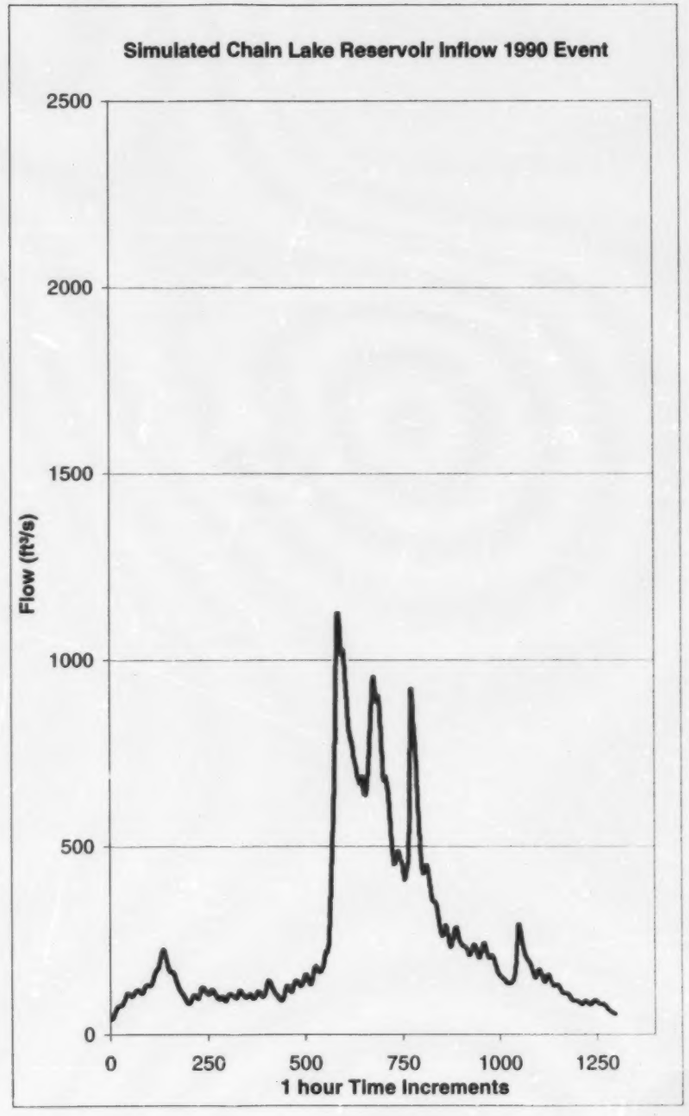




1990 Calibration Period: 01 May 03:00 – 30 June 03:00

## 2C: Chain Lakes Reservoir Inflows

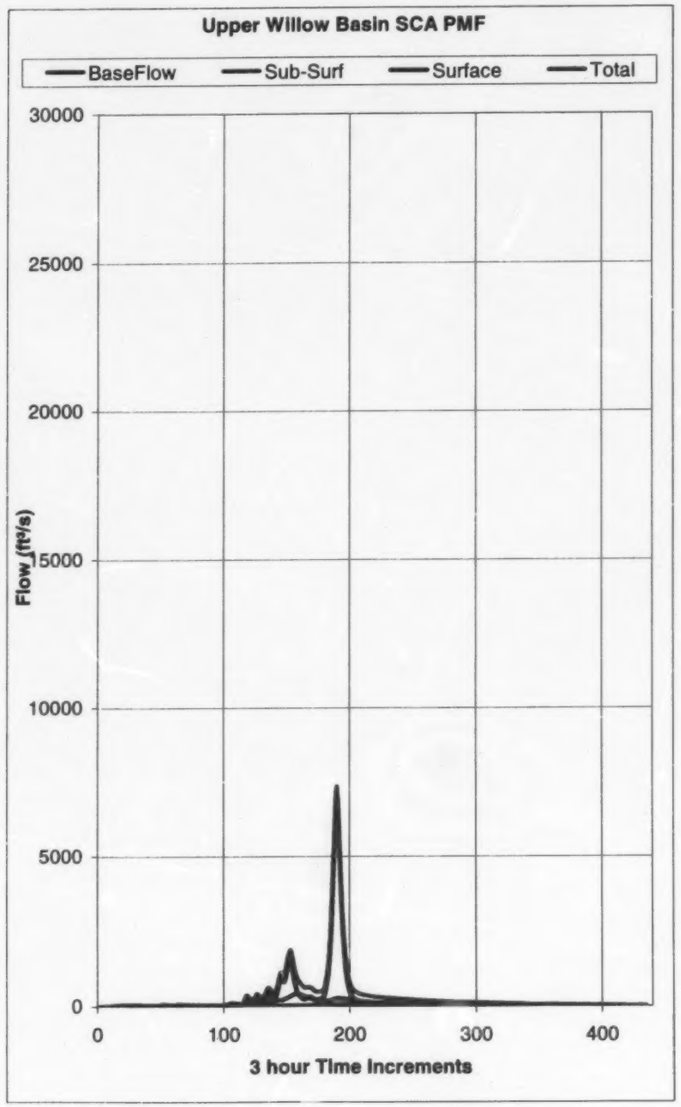


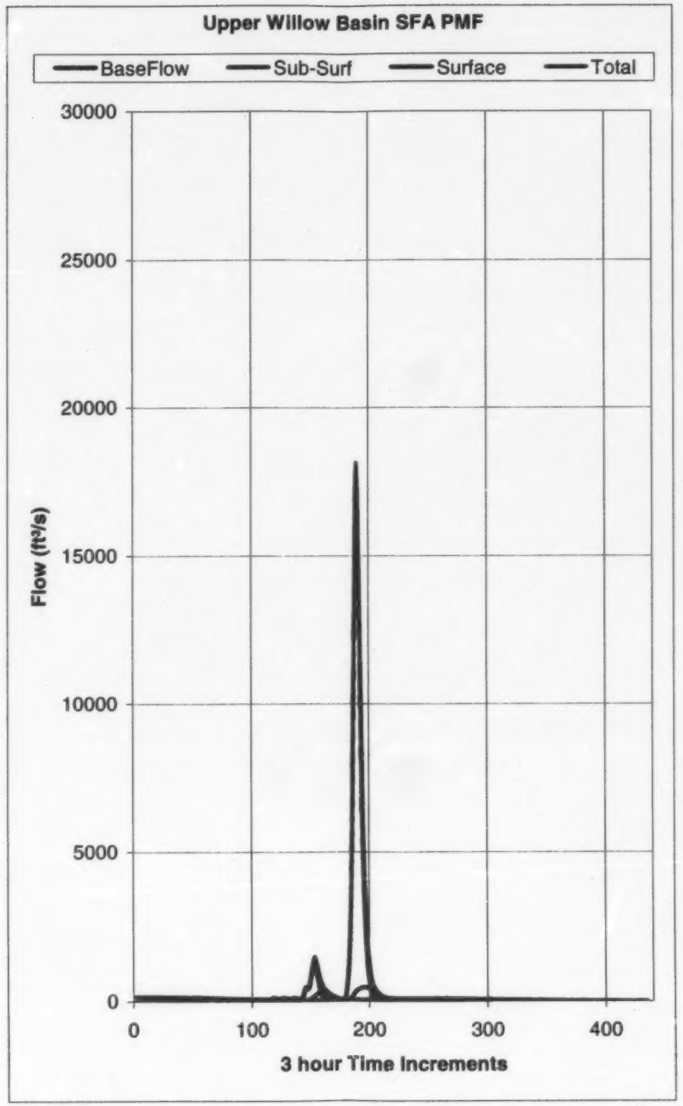



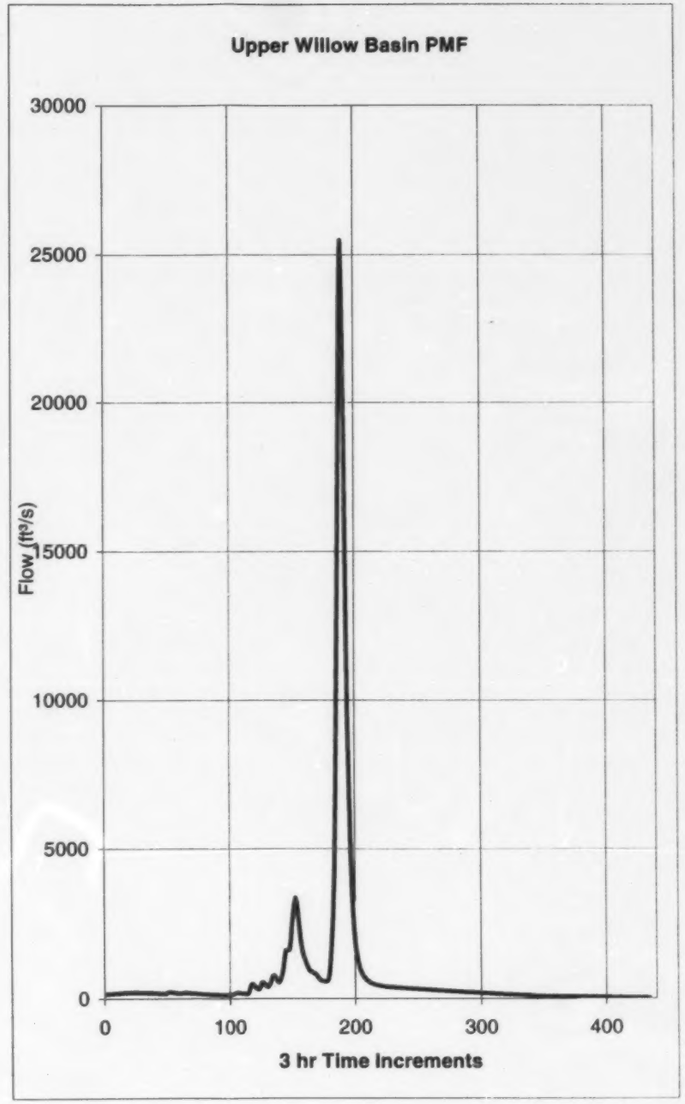



## APPENDIX 3: BASIN RESPONSE TO PMP

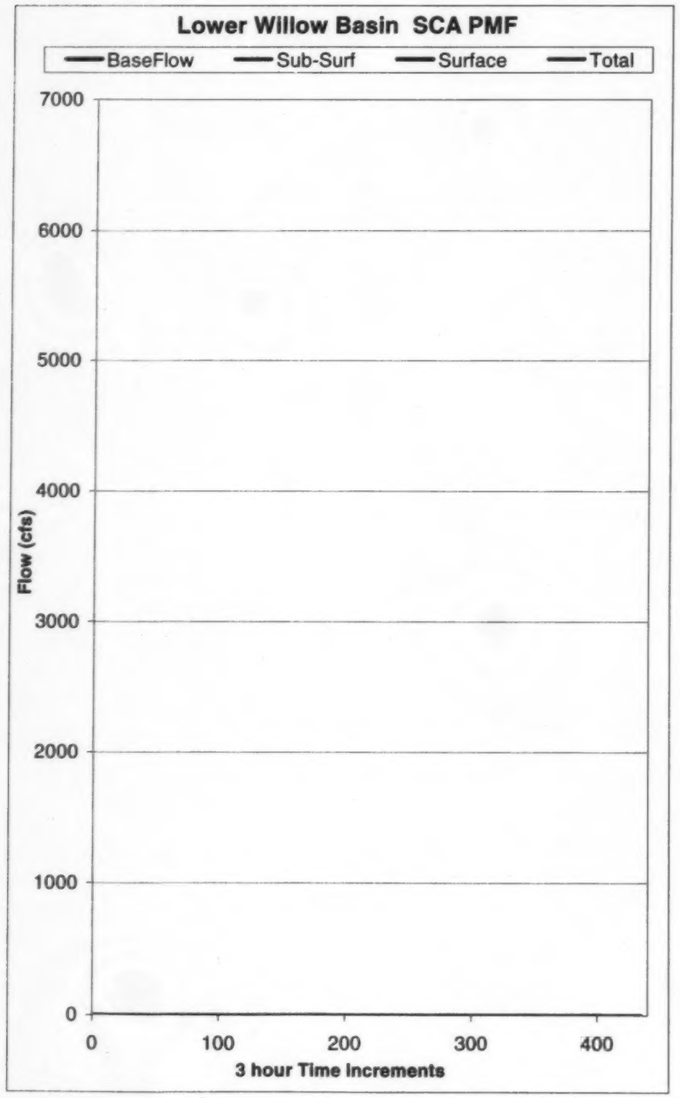
## 3A: Upper Willow Basin

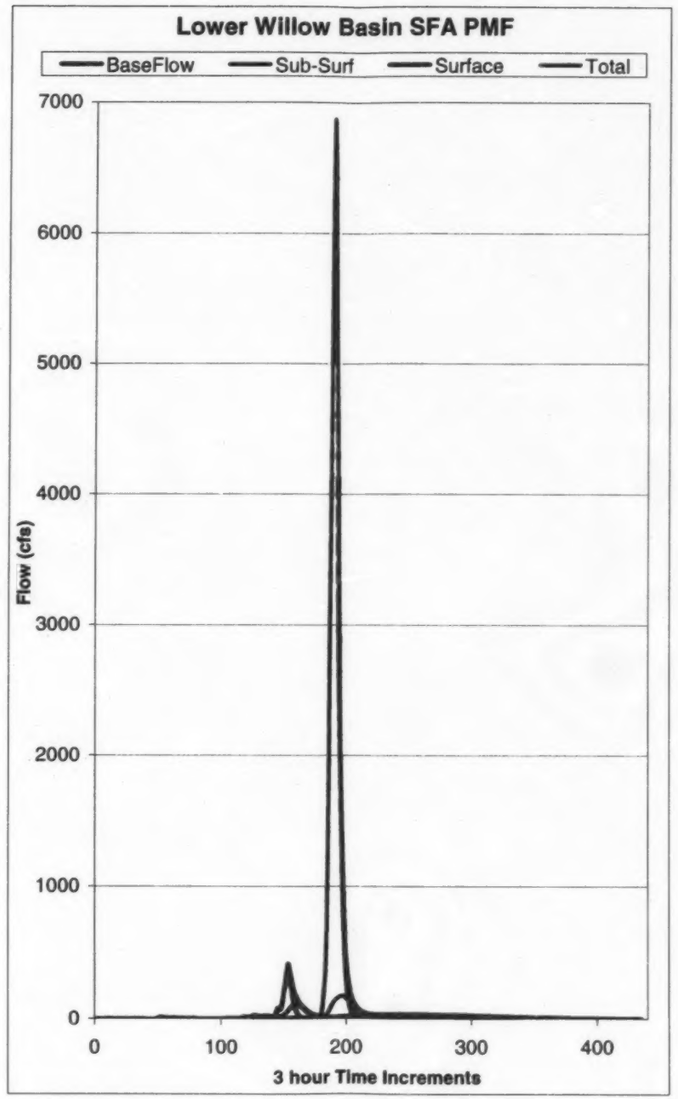


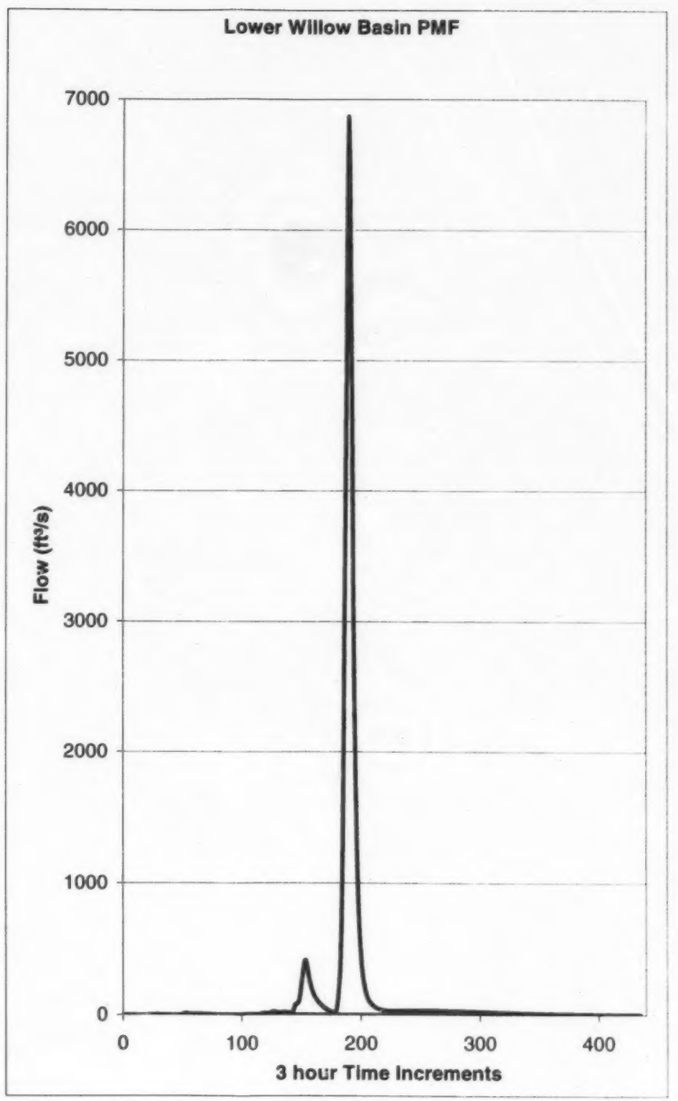



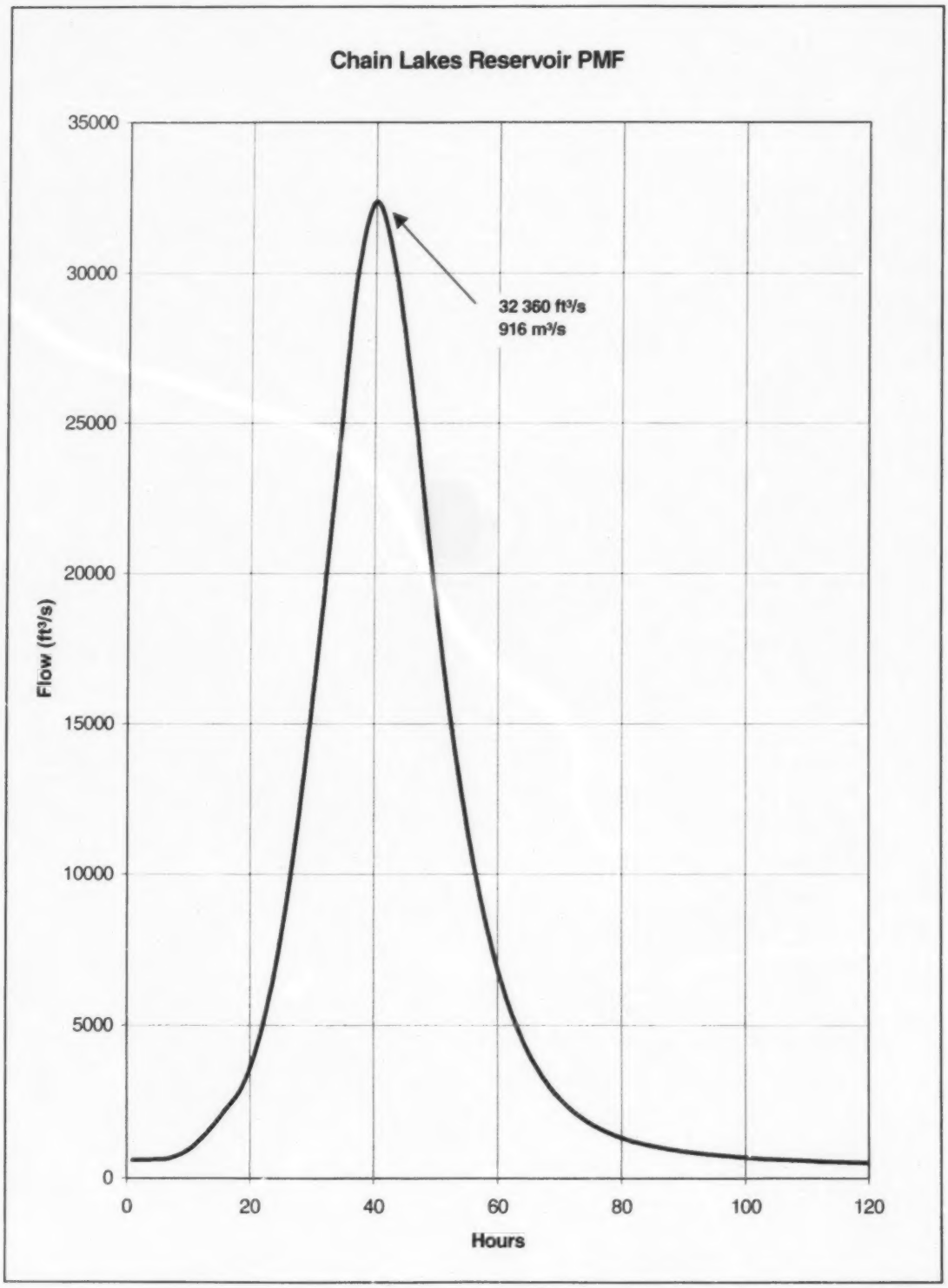
## 3B: Lower Willow Basin



## 3C: Probable Maximum Flood Chain Lakes Reservoir



# APPENDIX 4: COMBINED AND CONVERGENCE STORM MAXIMIZATION AND TRANSPOSITION

## 4A: Convergence Storm – June 15, 1973 Storm (Center A)

Depth-Area-Duration (mm)

| Area ($mi^2$) | 6hr | 12hr | 24 hr | 39 hr(storm) |
|---|---|---|---|---|
| 100 | 77.72 | 124.97 | 190.25 | 217.93 |
| 200 | 77.27 | 123.7 | 188 | 215.9 |
| 300 | 76.45 | 122.94 | 186.7 | 214.63 |
| 400 | 76.2 | 121.92 | 185.42 | 213.36 |
| 500 | 75.18 | 121.41 | 184.4 | 212.09 |
| 600 | 74.93 | 120.9 | 183.64 | 211.33 |
| 700 | 74.42 | 120.4 | 182.88 | 210.06 |
| 800 | 74.17 | 119.38 | 181.61 | 208.28 |
| 900 | 73.66 | 118.11 | 180.59 | 206.76 |
| 1000 | 73.14 | 116.84 | 179.58 | 205.23 |
| 2000 | 67.31 | 108.46 | 165.61 | 189.99 |

Statistics of Upwind Meteorologic Stations

| Station Name | Vermilion | Coronation |
|---|---|---|
| Elevation (m.asl) | 619 | 717 |
| Pressure (mb) | 942 | 930 |
| Recorded 12 hr Persisting DewPoint (°C) | 12.2 | 11.7 |
| Recorded 12 hr p.d.p. adjusted to 1000 mb (°C) | 15.3 | 15.7 |

Average 1000mb, 12 hr p.d.p. for upwind stations = 15.5°C

Maximum 1:100 yr, 1000mb, 'n' hr p.d.p. in °C for June 14 to July 17 (+/-15 days about storm); 12hr =22.5, 24 hr = 21.6, 39 hr = 21.2 ,

Average pressure level of storm area = 935 mb

Storm Maximization Ratio

| | | | |
|---|---|---|---|
| Precipital water at 15.5 °C and 300mb | = | 34.5 | mm |
| Precipital water at 15.5 °C and 935 mb | = | 7 | mm |
| | | 27.5 | |

12 hr Maximization

| | | | |
|---|---|---|---|
| Precipital water at 22.5 °C and 300mb | = | 64.5 | mm |
| Precipital water at 22.5 °C and 935 mb | = | 10.75 | mm |
| | | 53.75 | |

12 hr maximization ratio = 53.8/27.5 = 1.95

24 hr Maximization

| | | | |
|---|---|---|---|
| Precipital water at 21.6 °C and 300mb | = | 60 | mm |
| Precipital water at 21.6 °C and 935 mb | = | 10.3 | mm |
| | | 49.7 | |

24 hr maximization ratio = 49.7/27.5 = 1.81

36 hr Maximization

| | | | |
|---|---|---|---|
| Precipital water at 21.2 °C and 300mb | = | 58 | mm |
| Precipital water at 21.2 °C and 935 mb | = | 10.1 | mm |
| | | 47.9 | |

36 hr maximization ratio = 47.9/27.5 = 1.74

1000 mb Transposition Ratio

| | | | |
|---|---|---|---|
| Precipital water at 22.5 °C and 300mb | = | 64.5 | mm |
| Precipital water at 22.5 °C and 1000 mb | = | 0 | mm |
| | | 64.5 | |

| | | | |
|---|---|---|---|
| Precipital water at 22.5 °C and 300mb | = | 64.5 | mm |
| Precipital water at 22.5 °C and 935 mb | = | 10.75 | mm |
| | | 53.75 | |
| 1000 mb transposition ratio = 64.5/53.8 | = | 1.2 | * |

* NOTE - the transposition ratio 1.20 is applied to all durations

Maximization and Transposition Ratios

12 hr duration = 1.95 x 1.20 = 2.35
24 hr duration = 1.81 x 1.20 = 2.17
36 hr duration = 1.74 x 1.20 = 2.09

June 14 to July 17, 1973 Storm (Center A) Maximized by Variable Maximization Ratio and Transposed to 1000 mb Depth-Area-Duration in mm

| Area ($mi^2$) | 6 hr | 12 hr | 24 hr | 39 hr (storm)* |
|---|---|---|---|---|
| 100 | 182.3 | 293.1 | 434.7 | 492.5 |
| 200 | 181.2 | 290.1 | 429.6 | 487.9 |
| 300 | 179.3 | 288.4 | 426.6 | 485.0 |
| 400 | 178.7 | 286.0 | 423.7 | 482.1 |
| 500 | 176.3 | 284.8 | 421.4 | 479.2 |
| 600 | 175.7 | 283.6 | 419.6 | 477.5 |
| 700 | 174.5 | 282.4 | 417.9 | 474.7 |
| 800 | 174.0 | 280.0 | 415.0 | 470.7 |
| 900 | 172.8 | 277.0 | 412.5 | 467.2 |
| 1000 | 171.5 | 274.0 | 410.1 | 463.7 |
| 2000 | 157.9 | 254.4 | 378.3 | 429.3 |

* based on 36 hr precipitation

Project Area = 81.8 $mi^2$ = 211.86 $km^2$

1000 mb Convergence PMP by Variable Dew Point Procedure for a 212 $km^2$ Area

| Hours | 0-6 | 6-12 | 12-18 | 18-24 | 24-30 | 30-36 | 36-42 | 42-48 |
|---|---|---|---|---|---|---|---|---|
| Accumulated PMP (mm) | 182 | 293 | 374 | 435 | 467 | 493 | 498 | 502 |
| Incremental PMP (mm) | 182 | 111 | 81 | 61 | 32 | 26 | 5 | 4 |

## 4B: Combined Storm – June 5, 1964 Storm Center (Zone D)

Depth-Area-Duration (mm)

| Area ($mi^2$) | 6 hr | 12 hr | 18 hr | 24hr | 30 hr | 36 hr | 42 hr |
|---|---|---|---|---|---|---|---|
| 10 | 132.1 | 251.5 | 325.1 | 375.9 | 406 | 419.1 | 423 |

Statistics of Upwind Meteorologic Stations

| | |
|---|---|
| Station Name | Montana |
| Elevation (m.asl) | |
| Pressure (mb) | |
| Recorded 12 hr Persisting DewPoint (°C) | |
| Recorded 12 hr p.d.p. adjusted to 1000 mb (°C) | 16.7 |

Average 1000mb, 12 hr p.d.p. for upwind stations = 16.7°C

Maximum 1:100 yr, 1000mb, 'n' hr p.d.p. in °C for May 20 to June 23 (+/-15 days about storm); 12hr =21.2, 24 hr = 20.3, 36 hr = 19.9 , 48 hr =19.5 (18hr est = 20.7, 30hr est=20.1)

Average pressure level of storm area = 785 mb (7000ft)

Storm Maximization Ratio

| | | | |
|---|---|---|---|
| Precipital water at 16.7 °C and 300mb | = | 38.8 | mm |
| Precipital water at 16.7 °C and 785 mb | = | 21.9 | mm |
| | | 16.9 | |

12 hr Maximization

| | | | |
|---|---|---|---|
| Precipital water at 21.2 °C and 300mb | = | 58 | mm |
| Precipital water at 21.2 °C and 785 mb | = | 29.85 | mm |
| | | 28.15 | |

12 hr maximization ratio = 28.15/16.9 = 1.67

18 hr Maximization

| | | | |
|---|---|---|---|
| Precipital water at 20.7 °C and 300mb | = | 55.5 | mm |
| Precipital water at 20.7 °C and 785 mb | = | 28.9 | mm |
| | | 26.6 | |

18 hr maximization ratio = 26.6/16.9 = 1.57

24 hr Maximization

| | | | |
|---|---|---|---|
| Precipital water at 20.3 °C and 300mb | = | 53.5 | mm |
| Precipital water at 20.3 °C and 785 mb | = | 28.1 | mm |
| | | 25.4 | |

24 hr maximization ratio = 25.4/16.9 = 1.50

30 hr Maximization

| | | | |
|---|---|---|---|
| Precipital water at 20.1 °C and 300mb | = | 52.5 | mm |
| Precipital water at 20.1 °C and 785 mb | = | 27.7 | mm |
| | | 24.8 | |

30 hr maximization ratio = 24.8/16.9 = 1.47

36 hr Maximization

| | | | |
|---|---|---|---|
| Precipital water at 19.9 °C and 300mb | = | 51.6 | mm |
| Precipital water at 19.9 °C and 785 mb | = | 27.3 | mm |
| | | 24.3 | |

36 hr maximization ratio = 24.3/16.9 = 1.44

42 hr Maximization

| | | | |
|---|---|---|---|
| Precipital water at 19.5 °C and 300mb | = | 50 | mm |
| Precipital water at 19.5 °C and 785 mb | = | 26.5 | mm |
| | | 23.5 | |

42 hr maximization ratio = 23.5/16.9 = 1.39

Maximization and Transposition Ratios

| | |
|---|---|
| 12 hr duration = | 1.67 |
| 18 hr duration = | 1.57 |
| 24 hr duration = | 1.50 |
| 30 hr duration = | 1.47 |
| 36 hr duration = | 1.44 |
| 42 hr duration = | 1.39 |

June 5 to June 8, 1964 Storm Center Maximized by Variable Maximization Ratio and Transposed to 1000 mb Depth-Area-Duration in mm

| Hours | 6 | 12 | 18 | 24 | 30 | 36 | 42 | 48 |
|---|---|---|---|---|---|---|---|---|
| Accumulated PMP (mm) | 221 | 420 | 536 | 612 | 657 | 675 | 680 | 682 |